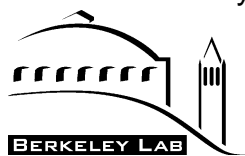


WATER HEATERS AND HOT WATER DISTRIBUTION SYSTEMS

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
Lawrence Berkeley National Laboratory



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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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- • Environmentally Preferred Advanced Generation
- • Industrial/Agricultural/Water End-Use Energy Efficiency
- • Renewable Energy Technologies
- • Transportation

Water Heaters and Hot Water Distribution Systems is the final report for the Develop Recommendations to Improve Hot Water Equipment and System Efficiencies in California Homes project (contract number 500-05-007,) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to PIER's Buildings End-Use Energy Efficiency Program.

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Abstract

This project conducted research to improve the efficiency of water heaters and hot water distribution systems in California. The three general areas were to develop:

- standard change proposals for the 2008 Title-24 Building Energy Efficiency Standards;
- a plan to successfully bring a super efficient gas water heating appliance to market;
- a plan to assess the energy savings potential of improvements of Hot Water Distribution Systems (HWDS) in existing single-family residences.

This final report does not cover the research results of all the diverse tasks of this project in detail. Only the broadest, most general findings are discussed in this report. The full details of the individual tasks are covered in individual task reports attached to this final report.

Proposals were submitted to the Commission's standards office for changes in Title 24 to : modeling tankless water heaters to account for the impact of small hot water draws and heat exchanger “cool down”; the Distribution System Multiplier and eligibility requirements for various residential hot water distribution systems to accurately reflect their performance; the mandatory requirements for parallel piping hot water distribution systems to more explicitly define acceptable installation; and the analysis of energy efficiency measures that reduce consumption of hot water to include the cost of saved water.

Proposals for changes to the Uniform Plumbing Code (UPC) were submitted to the International Association of Plumbing and Mechanical Officials (IAPMO) to: distinguish between hot and cold water distribution systems, use the diversity factors for multiple bathrooms as the standard method of design, require all hot water piping be insulated, and require all buried water piping be installed in waterproof conduits.

The Super Efficient Gas Water Heating Appliance Initiative (SEGWHAI) was developed under a separate contract (500-05-010). This project provided support for SEGWHAI and modeled how efficient a replacement water heater could be without unconventional or condensing designs.

This project also included a literature review of previous HWDS studies, assessed available sensing and monitoring technologies, and added questions about hot water use to a water utility survey on household water use.

A total of fifteen reports describing the findings of the research undertaken for this project are attached.

Keywords: water heaters, hot water, hot water distribution systems, Super Efficient Gas Water Heating Appliance Initiative, SEGWHAI, building energy efficiency codes, plumbing codes, energy efficiency, Energy Factor

Executive Summary

This project supported the Title-24 2008 Standards development process, supported the Super Efficient Gas Water Heating Appliance Initiative, and assessed the potential for energy savings in existing residential Hot Water Distribution Systems. Because of the extensive nature of the studies involved in the project, this report contains only a summary of the findings from each of the studies. Detailed reports from each of the tasks are attached as appendices.

The task to support the Title-24 2008 Standards development process included; Multi-Family Water Heating, Pipe Heat Loss Testing, Characterize Single Family Water Heating Construction Practice, Collect Supporting Information for the 2008 Standards Development Process, Validate HWDS Simulation Models, and Complete CASE Initiatives for Single Family Water Heating.

A survey on construction practices, pricing and availability and a field report on controls performance were done for Multi-Family Water Heating. Pipe heat loss tests were done on both bare and insulated pipe buried in damp sand. Water heating in single family construction was characterized with a construction practice survey, a materials and suppliers survey, and a review of current trends in California single family new construction. Prototypical house plans were developed for evaluating the efficiency of hot water distribution systems. The research teams collected information on hot water draw patterns from field studies, on water and wastewater tariffs, on ground heat transfer algorithms, and on tankless gas water heater performance. A hot water distribution system simulation model was validated. CASE initiatives were completed for tankless gas water heaters, for revised distribution system multipliers, and for water and wastewater tariffs for the Title-24 2008 Standards.

Tools and reports for future programs to accurately calculate the potential energy savings from improvements to hot water distribution systems in existing single family homes were developed. Questions to get a better understanding of hot water distribution systems were added to a survey for a California Single-Family Residential Water Use Efficiency Study. In response to the data needs of regulatory organizations proposals were submitted to change the current plumbing codes to better cover hot water distribution systems. A literature review of previous studies was undertaken to assess potential sensing and monitoring technologies. Key elements of sensing and monitoring technologies were bench tested.

1.0 Introduction

1.1. Background and Overview

The energy to heat water accounts for 31% of residential site energy use in California and 44% of residential gas use in California (KEMA-XENERGY, 2004). Hot water accounts for about 40% of indoor water use (DeOreo and Mayer, 2002). Clearly these are significant uses of energy and water, and should be investigated for potential savings. The overall goal of this project was to improve the efficiency of water heaters and hot water distribution systems in California.

There were three general objectives of this project:

- to develop standard change proposals for water heating in the 2008 Title-24 Building Energy Efficiency Standards;
- to plan an initiative to successfully bring a super efficient gas water heating appliance to market; and
- to plan a program to assess the energy savings potential of improvements to Hot Water Distribution System (HWDS) in existing single-family.

Many groups were involved in different parts of this project. Heschong Mahone Group did field research and developed recommendations for central hot water distribution systems in multifamily buildings. Applied Energy Technology Company conducted laboratory studies on the steady state and delivery phase heat loss from hot water pipes. Davis Energy Group and Chitwood Energy Management did a field survey of hot water distribution systems in new houses. Lawrence Berkeley National Laboratory (LBNL) surveyed suppliers about sales of materials and equipment for hot water distribution systems in new California construction. Oak Ridge National Laboratory (ORNL) researched current trends in California single family new construction that impact hot water distribution systems. Davis Energy Group developed prototypical floor plans of new California single family homes for use in code development efforts. LBNL collected hot water use patterns from previous studies, gathered water and wastewater prices from several dozen locations in California, and reviewed the existing literature from related fields on algorithms to determine heat loss from buried pipes. Davis Energy Group did field and laboratory testing of tankless gas water heater performance. ORNL studied the effects of increased pressure loss from reducing the pipe diameter in hot water distribution systems. Davis Energy Group with Rasent Solutions and ORNL both developed computer models for simulating the operation of hot water distribution systems. LBNL advised and supported the SEGWHAI initiative mostly developed under a separate CEC contract, including a computer simulation of water heater energy losses. LBNL and Aquacraft modified a mail survey of household water use to include questions relevant to hot water distribution systems. ORNL worked with IAPMO to develop change proposals for the Uniform Plumbing Code to improve the design of single family hot water distribution systems. ORNL reviewed possible sensing and monitoring technologies to use in studying hot water distribution systems and did a laboratory comparison of temperature sensor location outside and inside several hot water distribution piping materials.

Because of the extensive nature of the studies involved in the project, this final report contains only a summary of the findings from each of the studies. Detailed reports from each of the tasks are attached as appendices.

1.2. Project Objectives

The specific technical objectives for this project were to:

- Provide support to the Title-24 2008 Standards development process.
- Provide support for the Super Efficient Gas Water Heating Appliance Initiative.
- Assess the potential for energy savings in existing residential Hot Water Distribution Systems

1.3. Report Organization

This final report presents a summary of the deliverables submitted under this project. The individual reports are included as appendices. The organization this report is outlined following the three major tasks in the project. The three general tasks for this project were: 1) to develop standard change proposals for water heating in the 2008 Title-24 Building Energy Efficiency Standards, 2) to plan an initiative to successfully bring a super efficient gas water heating appliance to market; and 3) to plan a program to assess the energy savings potential of improvements to HWDS in existing single-family houses.

In Section 2, Project Approach, the activities that were undertaken as part of this project are discussed. The research approach to accomplish the project objectives varied for each task. This is discussed in this section.

In Section 3, Project Outcomes, the outcomes of and brief summaries of the findings from each task are described.

In Section 4, Conclusions and Recommendations, the conclusions from the research tasks and recommendations for future research activities are discussed.

The final sections are references and glossary.

2.0 Project Approach

This project approach section summarizes the approach of each of the three major tasks and all the subtasks.

2.1. Development of Hot Water Distribution System Recommendations for the 2008 Title-24 Residential Building Energy Efficiency Standards

The objective of this task was to develop residential building design standards recommendations to improve the energy efficiency of hot water distribution systems. This work specifically focused on developing standard change proposals for the 2008 Title-24 Building Energy Efficiency Standards (2008 Standards).

The task's work scope involved the following subtasks; Multi-Family Water Heating, Pipe Heat Loss Testing, Characterize Single Family Water Heating Construction Practice, Collect Supporting Information for the 2008 Standards Development Process, Validate HWDS Simulation Models, and Complete CASE Initiatives for Single Family Water Heating. The approach for each subtask is described in the following subsections.

2.1.1. *Multi-Family Water Heating*

To collect current market data, HMG conducted telephone surveys of architects, developers, engineers, energy consultants, building departments, contractors, and distributors. HMG also conducted site visits to multifamily project sites and building departments. The overarching aim of the study was to identify the most practical and cost-effective set of recommendations for controls in recirculation loops of central DHW systems in multifamily buildings. This survey work had two objectives; to characterize existing multifamily water heating design practice and to characterize existing boiler installations (with storage systems)

The surveys were conducted from January to June of 2006. There were two distinct survey instruments: one for current market practices and the other for price and availability. For the current practices survey architects, developers, and building departments were contacted. For the price and availability survey, the information was gathered through telephone surveys of plumbing contractors and distributors.

2.1.2. *Pipe Heat Loss Testing*

The objective of this subtask was to expand the basic knowledge of the behavior of hot water in pipes for various materials, flow rates, and environmental conditions. The parameters of interest were heat loss during steady-state flow, thermal decay with no flow, and delay times for hot water arrival at the beginning of a draw.

Tests were performed on both bare and insulated $\frac{3}{4}$ inch rigid CU pipe buried in damp sand. The water waste while waiting for hot-enough-to-use water to arrive at fixtures, expressed as the actual flow/pipe volume (AF/PV) ratio was calculated for bare buried pipe compared to bare pipe in air at flow rates less than 2 GPM.

A buried pipe test fixture was fabricated and installed in the test laboratory. The fixture consisted of a large plastic-lined wooden box measuring 24 feet long, 8 feet wide, and 4 feet deep. The box was filled with 25.5 tons of washed sand, to a depth of approximately 30 inches.

The initial tests were performed on ¾ inch nominal diameter rigid copper tubing. A direct thru-the-wall compression fitting immersion thermocouple approach was used to measure water temperatures. For this test, the U-shaped pipe layout was designed so that the distance between pipe and fixture side-walls, and between adjacent pipe heat-affected zones in the sand was a minimum of 2 feet. This resulted in the two legs of the U-layout being spaced 4 feet apart. Burial depth was 15 inches, resulting in a minimum of 15 inches of sand above and below the pipe. Total buried pipe length was approximately 48.5 feet. For each test, the inlet section was primed with hot water prior to opening a valve to the test section and initiating a draw.

2.1.3. Characterize Single Family Water Heating Construction Practice

The objective of this subtask was to develop recommendations to revise the prototypical house plans and plumbing layouts to be used in the 2008 Standards analysis.

To better understand how HWDS are being installed, Chitwood Energy Management and Davis Energy Group completed a field survey of sixty new production homes. The goal of the field survey was to quantitatively characterize the HWDS plumbing layout as well as to collect data on the type of water heater being installed, hot water fixture characteristics, and gather anecdotal feedback from plumbers and building superintendents on industry trends.

LBNL attempted to collect information by telephone and written surveys from trade associations, manufacturers, and builders about current practices for types of hot water distribution systems used in recent residential construction in California. The information was sought as a counter point for other data gathered in this project.

ORNL conducted a search of the internet and other sources to identify available data on new California single family home characteristics that would impact the design and operation of HWDS. The sources included the U.S. Census Data 2004 for the Western Region, several major California homebuilders' and the National Association of Home Builders Research Center (NAHBRC). The California specific Census data was of limited use except to define the number of occupants per household and the size of overcrowded households. The house size and other key features were gathered from plans on the major California homebuilders' websites. California specific Census Data was limited. It focused on occupant demographics and when data on the housing was included it was of the entire housing stock – not new homes. This made the California specific data of limited use except to define the number of occupants per household and the size of overcrowded households. Information on the use of plumbing fixtures and piping was obtained from a survey of California builders by the NAHBRC.

Davis Energy Group developed six prototype floor plans with “typical” hot water distribution system layouts based on real production home floor plans. The six selected floor plans were either part of the sixty sample field survey or were previously analyzed as part of the 2005 Title 24 Standards process for water heating distribution system performance.

2.1.4. Collect Supporting Information for the 2008 Standards Development Process

The objective of this subtask was to provide supporting information that will facilitate enhancements to the 2008 Standards to improve the energy efficiency of HWDS. The supporting information included: an improved hot water draw schedule to use in the Alternative Calculation Method (ACM)-based analysis of water heating energy use; a statewide database of water and wastewater costs to value the water savings benefits of alternative distribution system configurations; a collection of analytical heat loss models from other fields of study to complement the underground pipe heat loss testing; part load performance curves for instantaneous gas water heaters; and pressure loss calculations for residential HWDS with reduced pipe diameters.

LBNL collected hot water use data from several studies of single-family residences in recent years. Although none of these studies were done to find hot water draw patterns, the data collected in these studies was used to determine the volume of hot water use, number of draws and time since previous draw. This data was also examined to determine the relation between these parameters and the number of people in the house and the floor area of the house.

LBNL collected water and waste water tariffs in California cities and counties where there is a high level of new residential construction. Data from the Construction Industry Research Board on the number of new single family homes and units of multi-family housing built in each California city and the unincorporated areas of each county was used to target high growth areas of the state. Current water and waste water tariffs for these areas were collected from websites or directly contacting the utility.

A list of studies of heat transfer algorithms and models devised for generalized, hot water distribution system, ground-source heat pump and ground heat exchanger, nuclear waste repository, buried oil pipeline, and underground electricity transmission cable applications that could be adapted to computer simulation of under-slab hot water piping were collected by LBNL.

Davis Energy Group collected data from an occupied house being monitored under the Building America program to document field performance of a tankless gas water heater. A second tankless unit was tested at their shop facility to support field findings and facilitate data collection under more controlled conditions.

ORNL investigated the extent to which hot water pipe size could be reduced without exceeding acceptable pressure losses and without exceeding hot water velocity limits. The six homes used in the Title 24, 2008 revision analysis were used in this analysis as they represent a cross section of new home construction in California. Friction losses and water velocities for various pipe sizes of hot water lines were calculated and included both the hot water trunk and branches. The largest pipes analyzed were those dictated by the UPC. In addition smaller combinations of trunks and branches were evaluated as were differing pipe materials (copper, CPVC, and PEX).

2.1.5. *Validate HWDS Simulation Models*

The objectives of this subtask were to improve the HWDS analytical tool used in the Standards development and compliance processes, to make these tools publicly accessible, and to develop the appropriate program documentation.

Davis Energy Group originally developed the HWSIM hot water distribution model in 1990 as part of a California Energy Commission project to develop a comprehensive water heating methodology for the Title 24 Residential Standards. Due to project constraints, the original HWSIM program utilized some simplifying assumptions and had limited input flexibility in certain areas (e.g. the model was not able to simulate seasonal variations in inlet cold water temperature or variations in environment temperatures where the piping is run). This project allowed additional HWSIM development and provided validation results based on detailed laboratory pipe heat loss data collected by Applied Energy Technology.

ORNL has developed numerical model, using LabVIEW, to estimate the heat loss or gain from insulated and non-insulated hot water pipes. Heat loss from distribution piping affects overall energy use, water consumption, and homeowner waiting time at the end use points. During this project ORNL conducted ongoing model validation, documentation and user-friendliness improvement effort.

2.1.6. *Complete CASE Initiatives for Single Family Water Heating*

The objective of this subtask was to identify and document potential changes to the 2008 Title 24 Residential Building Standards. The documentation was submitted as CASE Initiatives.

Davis Energy Group proposed changes to the modeling of tankless gas water heaters under the Title 24 Residential Building Standards. Current ACM modeling rules for tankless water heaters overvalue their performance by not accounting for the impact of small hot water draws and heat exchanger “cool down” on overall performance. The proposed change is based on supporting information collected for the 2008 Standards Development Process for tankless water heaters.

Davis Energy Group proposed mandatory changes to the installation requirements for PEX parallel piping hot water distribution systems. The proposed change is based on supporting information collected for the 2008 Standards Development Process during the field study and use of the HWSIM modeling tool.

ORNL and Davis Energy Group proposed changes to modify the distribution system multipliers (DSM) for hot water distribution systems in Appendix RG of the ACM Manual. These recommendations stem from the review and evaluation of information and analyses prepared as part of previous work. A numerical model for residential hot water distribution systems developed by ORNL was used to analyze various types of pipe, with and without insulation.

LBNL proposed that the cost savings of saved water be included in the cost/benefit analysis of measures which save hot water. This was based on water and waste water tariffs in California

cities and counties collected as supporting information for the 2008 Standards Development Process.

2.2. Support for the Super Efficient Gas Water Heating Appliance Initiative (SEGWHAI)

The objective of this task was to provide technical support and program leadership to the SEGWHAI, which was to generate the necessary market pull and foster partnerships to develop cost-effective replacement water heaters with energy savings of approximately 30% compared to new conventional units. The PIER Natural Gas Buildings Program supported the SEGWHAI by funding the first year technical and market analyses necessary to successfully launch this multi-year initiative. The R&D project was PIER-Natural Gas Contract No. 500-05-010. This task funded the participation of LBNL in PIER's Natural Gas SEGWHAI project.

2.2.1. *Organizational Development for SEGWHAI*

The objective of this subtask was to assist in creating the organizations necessary to pursue the initiative to develop a super efficient gas water heating appliance. In collaboration with the PIER SEGWHAI project team, LBNL recommended and recruited knowledgeable experts to serve on the Project Steering Committee for SEGWHAI. LBNL provided technical advice to PIER's Natural Gas SEGWHAI Project.

2.2.2. *Develop Outreach Materials for Potential SEGWHAI Participants*

The objective of this task was to review the outreach materials developed to support recruiting of SEGWHAI participants primarily from California and then from North America.

2.2.3. *Assess Manufacturer Interest and Capabilities*

The objective of this task was to contact all of the major manufacturers of small storage volume natural gas water heaters in North America in a structured manner to assess their interest and capabilities for producing the next generation appliance. LBNL assisted with the Manufacturer Interest and Capabilities Assessment and reviewed the Draft Manufacturer Interest and Capabilities Survey.

2.2.4. *Establish the Technical Foundation for Gas Water Heater Technology Improvements*

The objective of this task was to establish the gas water heating appliance performance baseline upon which all SEGWHAI energy efficiency improvements were compared. LBNL prepared a Gas Water Heater Energy Losses report based on the TANK simulation model work LBNL did in support of the US DOE water heater appliance standards proceedings. LBNL reviewed and commented on the Draft Gas Water Heating Technical Foundation Report.

2.2.5. *Assess Potential for Energy and Environmental Benefits*

The objective of this task was to analyze the potential for energy and air quality benefits from likely pathways with technical, economic and achievable savings assessments. LBNL reviewed the Draft Energy and Environmental Benefits Report.

2.2.6. Assess California's Small Gas Storage Water Heater Market

The objective of this task was to develop a scope of work to assess California's small gas storage water heater market. This detailed assessment will not be completed in this Agreement, but the scope of work developed in this task will likely be executed in a future phase of SEGWHAI. LBNL reviewed the Draft Scope of Work for the California Small Gas Storage Water Heater Market Assessment.

2.2.7. Develop Roadmap for SEGWHAI Commercialization, Outreach and Marketing

The objective of this task was to develop a roadmap to the successful mass market implementation of SEGWHAI qualified units. LBNL reviewed and commented on the draft SEGWHAI Commercialization, Outreach and Marketing Roadmap.

2.2.8. Identify and Document Technical Pathways to Super Efficiency

The objective of this task was to identify and document the most likely technical approaches to accomplish 30% improvements in gas water heating energy performance with a reduction in NOx emissions needed to meet SCAQMD Rule 1121. LBNL reviewed and commented on the Draft Technical Pathways to Super Efficiency Water Heaters Report.

2.2.9. Develop Draft Technical Specifications

The objective of this task was to produce the draft technical specification that units must meet or exceed to qualify as SEGWHAI units. LBNL reviewed and commented on the Draft SEGWHAI Technical Specifications.

2.3. Existing Residential Hot Water Distribution Systems

The objective of this task was to assess the potential for energy savings from improvements to hot water distribution systems in existing single family homes. This work specifically focused on developing a future program to accurately calculate the energy savings potential.

2.3.1. Pilot mail survey of single-family house occupants

The objective of this subtask was to develop a broad understanding of the HWDS in single-family houses and occupant perceptions of those HWDS. This task was a pilot study for a much larger mail survey that will be done for subsequent studies. LBNL developed Existing Single Family HWDS Perceptions Survey questions that are included in a Household Water Use Survey. The questions ask about the occupant's perceptions of their HWDS. The survey will be administered to approximately 700 households as part of California Single-Family Residential Water Use Efficiency Study project sponsored by the California Department of Water Resources.

2.3.2. Determine data needs of regulatory organizations

The objectives of this subtask were to identify the data required to change the plumbing and other code(s) which impact HWDS design and installation and to determine how to generate these data.

2.3.3. *Assess potential sensing and monitoring technologies*

The objective of this subtask was to identify and evaluate sensing and monitoring technologies and techniques to support plumbing code changes related to HWDS. These sensing and monitoring technologies would be candidates for use in future field monitoring studies. ORNL reviewed the literature of previous HWDS monitoring studies and assessed available sensing and monitoring technologies.

2.3.4. *Bench test key elements of sensing and monitoring technologies*

The test objective was to determine the response time lag between a thermocouple in the fluid stream versus a thermocouple taped to the outside wall of a typical household water pipe at different pipe sizes and water flow rates. The testing included various pipe types and configurations.

3.0 Project Outcomes

This section briefly summarizes the findings in the deliverables from all project tasks. All reports have been delivered to the Energy Commission and are attached in full to this Final Report as appendices.

3.1. Development of Hot Water Distribution System Recommendations for the 2008 Title-24 Residential Building Energy Efficiency Standards

The scope of this task included the following subtasks; Multi-Family Water Heating, Pipe Heat Loss Testing, Characterize Single Family Water Heating Construction Practice, Collect Supporting Information for the 2008 Standards Development Process, Validate HWDS Simulation Models, and Complete CASE Initiatives for Single Family Water Heating. The outcomes of each subtask are described briefly below. For more details see the full reports included in the appendices.

3.1.1. Multi-Family Water Heating

California currently has about 50,000 multifamily unit starts every year. By 2010 the total number of multifamily units existing in California is projected to be 3.9 million. The California Energy Commission estimates that of these units, 40% are served by central DHW systems in climate zones 6 through 10, and 15% in the other climate zones.

Construction Practices, Pricing and Availability Survey Report

One finding of the study is that central domestic hot water systems are most prevalent in high rise buildings and in dense urban areas. The most common control types installed on the recirculation loops of the domestic hot water distribution systems are time controls, temperature controls, and time plus temperature controls. Demand controls and temperature modulation controls were not commonly installed by the survey respondents, so we conclude that they do not have significant market penetration at this time. Incorporating these control types into the California Energy Efficiency Standards as a performance option may increase market penetration and help to realize the potential energy savings.

Survey respondents usually claimed that insulation on recirculation loops is installed as mandated by the California Building Energy Efficiency Standards (Title 24). This is not easily verifiable because the recirculation pipes are often buried. Verification of the installation of insulation is necessary to realize the potential savings possible from controlling heat loss through the distribution pipes.

Controls Performance Field Report

Three buildings were surveyed and in each building three or four different control systems were installed for a one-week period—continuous pumping, timeclock control, demand control and temperature modulation control. Various water flow rates, water and air temperatures at

different locations, as well as burner run times were logged. The recorded data reveal differences in energy use and daily hot water draw patterns, and crossover flow issues.

This survey compared the energy savings from timeclock control, demand control and temperature modulation. The amount of energy saved depended on recirculation system configuration, control settings, and hot water draw pattern.

In all three buildings, under the demand control scheme, the hot water recirculation pump was switched on for less total time during the day, compared to timeclock control. As a result, heat loss through the recirculation loop was reduced. In some cases, the recirculation pump was not switched on even though there was demand and water temperature in the recirculation loop was relatively low. This was possibly due to sensor malfunction or incorrect control settings. In these cases, energy savings were large. However, higher total hot water draw was observed, since tenants had to run the hot water line for longer to obtain hot water.

The demand control system achieved higher savings in the smaller building than in the larger one. This is consistent with expectations because the demand control system achieves savings during periods of no demand, and larger buildings are less likely to have periods during which none of the occupants requires hot water.

Under temperature modulation control, the daily average hot water temperature was reduced, so the heat lost through the recirculation loop and storage tanks was also reduced. Similar percentage energy savings were observed for both buildings tested with temperature modulation control. The magnitudes of temperature modulation (i.e. the amount of setback) were similar for both sites.

For systems that were minimally Title 24 compliant the savings from advanced controls (demand, or temperature modulation) were 6%-16% of daily gas consumption. It should be noted that part of the energy saved was due simply to supplying hot water at lower temperatures, compared to the baseline condition in which we found each building. This means that the savings achieved in these buildings may not be replicated in other buildings that have more moderate supply temperatures.

Daily hot water draw schedule was also a focus of this study. The logged data show that the shape of the daily draw schedule curve is significantly flatter than the residential schedule in Title 24 2005. This indicates that the hot water draw was more evenly distributed throughout the day, instead of concentrated at peak hours. The draw schedules on weekdays were significantly different from that of weekends.

There have been reports from DHW controls manufacturers indicating the existence of “crossover” flows in hot water systems with recirculation, possibly in the following two forms:

- Reverse flow from the recirculation loop into the cold water lines, via the storage tank
- Flow between faucets (or other single-lever valves) via the cold water line

Crossover flow might be caused by the pressure differential between the hot water pipes and the cold water pipes created by recirculation pump (located next to the storage tank). This

pressure difference may force water to flow through faulty single-lever valves in the dwelling units that allow flow between the hot and cold water pipes. Therefore, a crossover loop is established that carries hot water into the cold water pipes and vice-versa through faulty single-lever valves. This type of flow may also be occurring through tempering valves, washing machines and other devices that are connected under pressure to both hot and cold water lines.

The experimental configuration did not allow direct measurement the second type of crossover flow (between faucets). Back flow was measured through the cold-water make-up line. Since the crossover flows are small and the measurement errors of ultrasonic flow meters are relatively high, the authors are not confident of the magnitude of energy losses from crossover flows. However, in one site, the energy loss was calculated to be 7% of total DHW energy. This potential loss of energy highlights the need for follow-up research on crossover flows.

Demand-controlled systems are likely to incur smaller crossover losses, since the recirculation pump is turned on less often. A check valve on the cold water supply line near storage tank would be a good solution for stopping back flow through the cold water supply line.

Proposed Multi-Family Water Heating Changes Codes and Standards Enhancement (CASE) Report

This report recommended three mandatory measures, one prescriptive requirement and two modeling changes to the 2008 California Building Energy Efficiency Standards for multifamily buildings. The recommendations are described in the Conclusions and Recommendations section of this report.

3.1.2. Pipe Heat Loss Testing

Tests have been performed on both bare and insulated $\frac{3}{4}$ inch rigid copper pipe buried in damp sand. Results show that piping heat loss rates for bare pipe in damp sand are on the order of 4 to 7 times higher than bare pipe in air. Moreover, the addition of $\frac{3}{4}$ inch thick R-4.7 foam insulation dramatically lowers buried pipe heat loss. The addition of the insulation appears to reduce heat loss by approximately a factor of 15-20 compared to bare buried pipe. In fact, the insulated buried pipe heat loss rates appear to be at least slightly lower than that of similarly insulated pipe in air.

The water waste while waiting for hot-enough-to-use water to arrive at fixtures, expressed as the actual flow/pipe volume (AF/PV) ratio appears dramatically higher for bare buried pipe compared to bare pipe in air at flow rates less than about 2 GPM (and probably at higher flow rates in longer pipes). This is due to high heat loss to the sand. At flow rates above 2 GPM, AF/PV ratios were similar to in-air piping for the short pipe lengths tested, because residence time in the pipe for any particular water particle is low, and hence temperature drop is also low at the higher flow rates. The addition of pipe insulation dramatically reduces pipe heat loss, resulting in AF/PV ratios of the insulated buried pipe being similar to similar bare and insulated pipe in air. In summary, placing uninsulated hot water distribution piping in a buried environment is highly energy inefficient. Adding insulation to buried hot water distribution piping substantially reduces energy waste, at least in damp, but not saturated environments.

3.1.3. Characterize Single Family Water Heating Construction Practice

The outcomes of this subtask were three surveys and reports along with prototypical house plans and plumbing layouts that could be used in the 2008 Standards analysis. The outcomes of the reports and surveys are summarized here. The prototypical house plans are described at the end of this section.

Single Family Water Heating Construction Practice Survey

The sixty houses surveyed included installations from 19 different plumbing contractors. Sites were geographically located as described in Table 1. The majority of the sites were located in climate zone 12. Although no sites were surveyed in the southern San Joaquin Valley, the geographic range in zone 12 extended from the San Francisco Bay Area commuting communities of San Ramon and Tracy eastward to El Dorado Hills in the Sierra foothills. Nine southern California coastal sites were surveyed as well as fifteen sites in the greater Palm Springs area.

Table 1. Site Location Summary

Climate Zone	Number Of Sites	Location
6	6	San Juan Capistrano, Costa Mesa
8	3	Tustin
10	1	Menifee
11	6	Lincoln, Redding
12	29	Woodland, El Dorado Hills, Elk Grove, Rancho Cordova, San Ramon, Tracy, Mountain House
15	15	Indio, Palm Springs, Desert Hot Springs

Conditioned floor area averaged 2,432 ft². Twenty-five of the houses were single story (average floor area equal to 2,209 ft²) and 35 were two-story (average floor area equal to 2,590 ft²). On average there were 2.84 bathrooms per house and 12.85 hot water use points. A total of 21,996 feet of pipe were measured in the sixty homes (average of 367 feet per house). PEX was the most common material installed (84% by length). None of the 35 houses surveyed north of the Tehachapis utilized copper as the primary piping material. In southern California, nine of the 25 systems were copper systems. No other piping materials besides copper and PEX were found. PEX has achieved significant market share in the last few years with a strong trend from copper piping to PEX piping. This was especially true in Northern California. All areas of the state where PEX is allowed show fairly rapid transition to this material. The input from plumbers who have switched to PEX is that the system is cheaper to install, can utilize less skilled labor, and is less prone to leaks.

Systems of all types were generally not efficiently installed. The following summarizes findings on each of the system types:

Trunk & Branch and Hybrid Systems

Eliminating excessive pipe length is most important improvement that could be implemented in both trunk & branch and the hybrid system types. Installers seem to put little value on reducing pipe length despite the benefits of reduced hot water waiting time (less callbacks). Designing a system with an emphasis on reducing piping length would have lower material costs, lower installation labor costs, and would provide better performance. For some reason installers tend to run trunks parallel to framing rather than straight to where the hot water is needed. This trend adds about 40% to the length of the trunk.

Parallel Piping - Manifold Systems

Eliminating excessive pipe length is also the most important improvement that can be made to parallel piping systems, but the improvement is much easier. The majority of the excess pipe length is found in the main between the water heater and the manifold. The water heater and the manifold are typically located adjacent to each other but the piping that connects the two is often routed by other than a direct route. In one case there was 24 feet of one-inch pipe between the water heater and the manifold. On average, reducing the observed length to a maximum of 10 feet would reduce the entrained volume of the manifold systems by 26%. (Reducing this length by running the main out the side of the manifold cabinet and directly to the water heater could reduce this length to about 3 feet.)

Another pipe length reduction opportunity exists for two-story houses. Some, but not all, plumbers tend to run the piping to the attic and then back down to the first floor – even if the draw point is only 10 feet away. The preferred approach would be to remain between floors.

One issue that needs further study is the energy impact of tightly bundling hot and cold piping together. This was seen in some cases. The bundling was apparently done to consolidate the tubing in one location and make the piping installation look better.

Hot Water Recirculation Systems

Eliminating excessive pipe length is also a major issue for recirculation systems. In fact the problem is more significant than for other system types since excess pipe length is usually large diameter piping (3/4" or 1"). For the twelve recirculation sites surveyed, the average recirc loop entrained volume was found to be 4.42 gallons. Return line sizing was found to average 0.99 gallons and runouts (from the loop to the fixtures) were 0.17 gallons on average. For continuous or timer controlled loops, the large loop size has significant energy impacts. For the preferred demand recirculation approach, the data reinforces the need to fully understand how these systems are installed and controlled.

The poorest performing systems in the recirculation sample appear to be the three systems that were designed as hot water circulation systems but the actual installation of the pump is an option. The circulation return line is terminated inside the wall so no one but the builder can install the optional circulation pump. From our vantage point, it did not appear that the recirculation loops were to be installed. Without a pump, these oversized lines would take a minimum of seven minutes to fill the hot water line to the kitchen sink.

Although parallel piping systems utilize roughly twice the length of piping relative to conventional plumbing practice, the entrained volume (per unit of floor area) was the least of the four system types. Additional significant volume reductions can be achieved with parallel piping systems by shortening the length of the main line between the water heater and the manifold. A 26% average volume reduction was calculated for the manifold systems if the length of the main could be reduced to 10 feet.

Title 24 eligibility criteria for all system types should be carefully reviewed to insure that the systems being installed are properly credited or penalized.

HWDS Materials and Equipment Suppliers Survey

Three groups were approached for information on residential hot water distribution systems. Of the eight associations queried, none have provided information. Of the twelve manufacturers/distributors, one has provided information. Of the eight builders, three have responded with information. Given that the respondents are not representative of their entire industries, the information received cannot be aggregated and conclusions drawn on current building practices or future building trends. No effort has been made to merge the builder information. Such effort should not be made since these responses cannot be assumed to represent building practices in California.

Current Trends in California Single Family New Construction

Based on Census Data and the housing currently on the market from major builders in California the six single-family houses described in Table 2 are suggested as reasonably representative of the 2005/2006 market in area, number of bedrooms, number of baths, and number of stories. The suggested number of occupants per house is shown in after the description. Assuming a uniform distribution, the following six house-types would yield an average of 2.8 persons per household average.

Table 2. Suggested Housing Characteristics

House 1.	~1200 SF	two bedrooms, two baths, single story, (perhaps a condo)	1 person
House 2.	1200-1999 SF	three bedrooms, two baths, single story	2 persons
House 3.	2000-2499 SF	three bedrooms, two & half bath, two stories	3 persons
House 4.	2000-2999 SF	four bedrooms, two & half bath, single story	3 persons
House 5.	3000-3999 SF	four bedrooms, three & half bath, two stories	4 persons
House 6.	4000-4999 SF	five bedrooms, five baths, two stories	4 persons

Taken as a uniformly distributed group these six houses somewhat exceed the area and number of bathrooms reflected in the 2004 housing characteristics data. However, data from the past 30 years indicates that these characteristics are steadily growing. Since these houses are intended to reflect conditions for the 2008 revision of Title 24, this increase was considered appropriate.

The number of persons per household which impacts both overall hot water consumption and the pattern of that consumption will vary from the suggested occupancy shown above. This will occur both between different houses of the same type and over time in any given house as families change in size and age.

In addition the Census data indicated that some California residences were “crowded” (6.1%) and “severely crowded” (9.1%). Given the potential broad range of occupancies it may be advisable to use both a “typical” and “high occupancy” water consumption rate and use pattern when evaluating the various options being considered in the revised Title 24.

The Census data also suggests that overcrowding is related to ethnic and economic status. It also observes that overcrowding is more pronounced in multifamily housing. These factors suggest that overcrowding may not need to be considered in larger, more costly homes. It is recommended that only Houses 1-3 be evaluated for overcrowding.

Single Family Prototype Floor Plans and Piping Layouts

Six prototype floor plans were developed with “typical” hot water distribution system layouts. All of the six prototypes are based on real production home floor plans. The six selected floor plans were either part of the sixty sample field survey or were previously analyzed as part of the 2005 Title 24 Standards process for water heating distribution system performance. Based on current new home construction characteristics, three of the floor plans were selected to be single story homes and the remaining three were selected as two-story. The selected floor area ranges were intended to bracket reasonable floor area ranges for one and two-story homes, respectively, and also provide a midpoint house size. Table 3 summarizes the six house plans.

Table 3. Description of Prototype Floor Plans

Plan Floor Area (ft²)	Number of Stories	Source of House Plan
1,367	One	2006 Sixty Home Survey
2,010	One	2005 Title 24 Evaluation
3,080	One	2005 Title 24 Evaluation
1,430	Two	2006 Sixty Home Survey
2,811	Two	2005 Title 24 Evaluation
4,402	Two	2006 Sixty Home Survey

Characterization of “typical” layouts was based on volumetric data reported in the sixty home field survey. The field survey report found that the average entrained volume for conventional trunk and branch plumbing systems was 0.49 gallons per 1,000 ft² of conditioned floor area. Using this as a goal, the plumbing layouts were generated. In some cases garage water heater locations were shifted to allow the resulting average volume to come in within 5% of the goal. The resulting layouts are presented in the attached report.

3.1.4. Collect Supporting Information for the 2008 Standards Development Process

The outcomes of this subtask provided supporting information to facilitate enhancements to the 2008 Standards to improve the energy efficiency of HWDS. The supporting information

included: an improved hot water draw schedule to use in the Alternative Calculation Method (ACM)-based analysis of water heating energy use; a statewide database of water and wastewater costs to value the water savings benefits of alternative distribution system configurations; a collection of analytical heat loss models from other fields of study to complement the underground pipe heat loss testing; part load performance curves for instantaneous gas water heaters; and pressure loss calculations for residential HWDS with reduced pipe diameters.

Hot Water Draw Patterns: Findings from Field Studies

Data was collected for 41 houses from five different field studies. The monitoring intervals ranged from 2 weeks to 27 months. Although this is not a large sample and the studies were not attempting to be statistically representative, the hot water draw patterns should be reasonably representative of California houses.

Volume of Hot Water Use

The average daily volume of hot water use among this sample of houses is 62.8 gallons. Most houses averaged between 20 and 80 gallons per day.

The average daily hot water use scales roughly with the number of residents in a house. However, there is a wide range of average hot water usage for houses with the same number of residents. Average daily use per person ranges widely from a low of 6 gallons per day to a high of 40 gallons per day.

The average daily hot water use correlates poorly with house area. Factors that may be responsible for variation in hot water use among similar-sized houses include the number of residents, the ownership of hot water-using fixtures and appliances (especially large uses of hot water such as a spa tubs), water heater inlet temperature, and variation in water use habits. Because these were not consistently recorded in every monitoring study, it was beyond the scope of this study to analyze these factors.

Patterns of Hot Water Use

Figure 1 shows the average hot water use over a 24-hour period for all of the sample houses as a fraction of daily total use. This hourly hot water use schedule shows that usage is highest in the morning and in the 5-9 p.m. period, when dinner is prepared and dishes are washed.

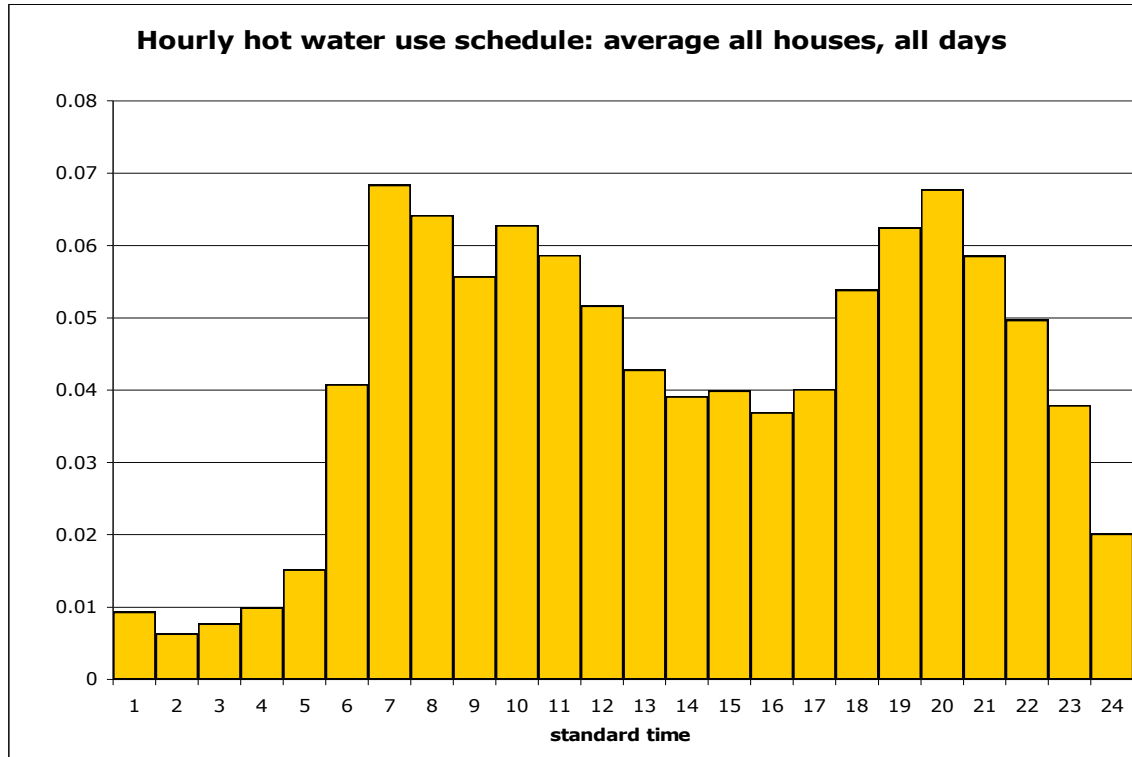


Figure 1. Hourly Hot Water Use

The hourly water heating schedule for weekdays exhibits more pronounced usage in the early morning. The hourly water heating schedule for weekend days shows, as one would expect, higher hot water use later in the morning.

Number of Draws

The average daily number of hot water draws among the sample houses is 46. Most sample houses averaged between 20 and 80 draws per day. Figure 2 shows the houses ranked by average number of draws per day.

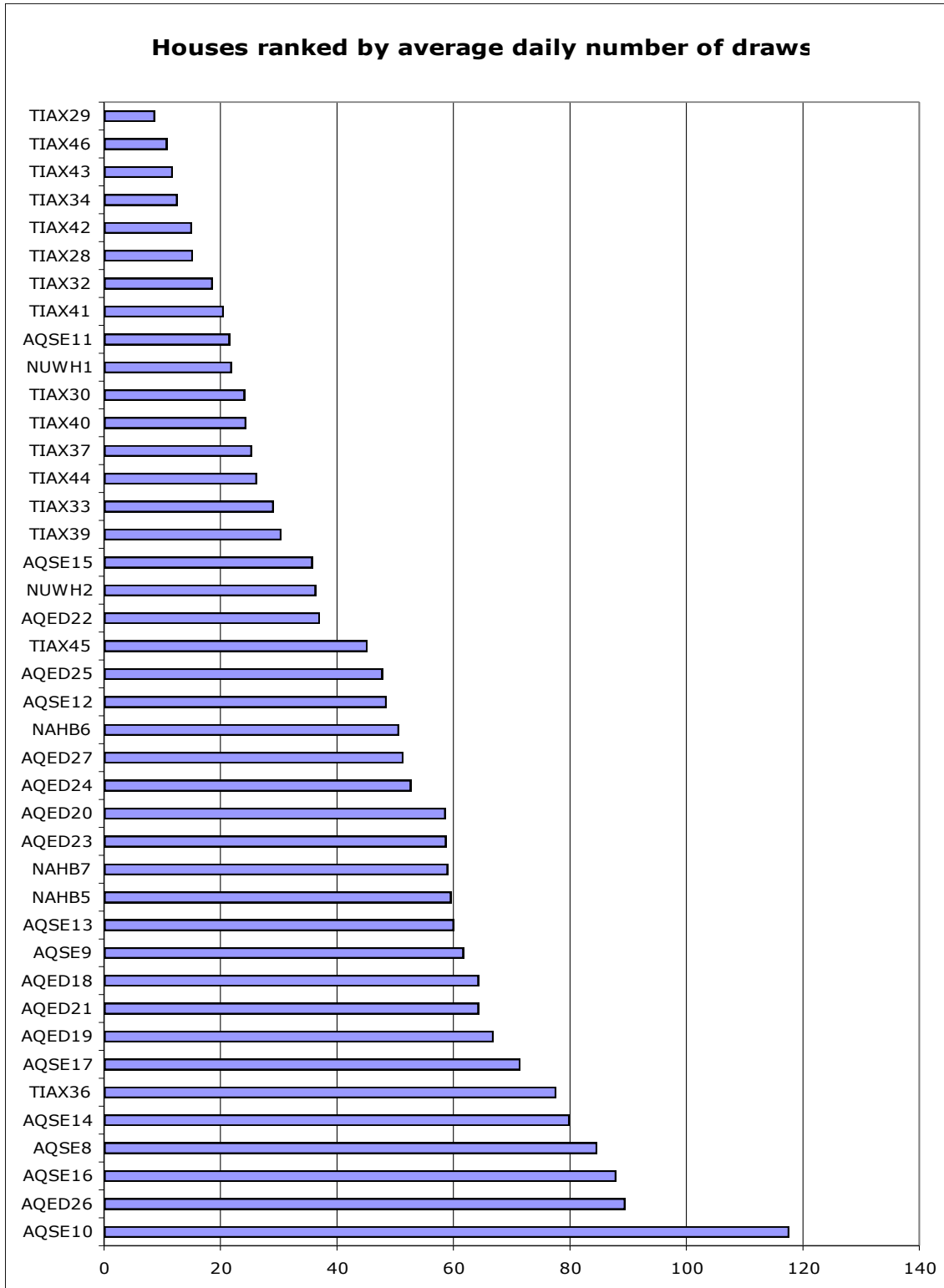


Figure 2. Average Daily Number of Draws by House

The average daily number of hot water draws roughly correlates with the number of residents in a house. As Figure 3 shows, there is a wide range of average hot water draws for houses with the same number of residents. Indeed, in this sample, many houses with two residents averaged more draws per day than houses with four residents. The average daily number of hot water draws correlates poorly with house area.

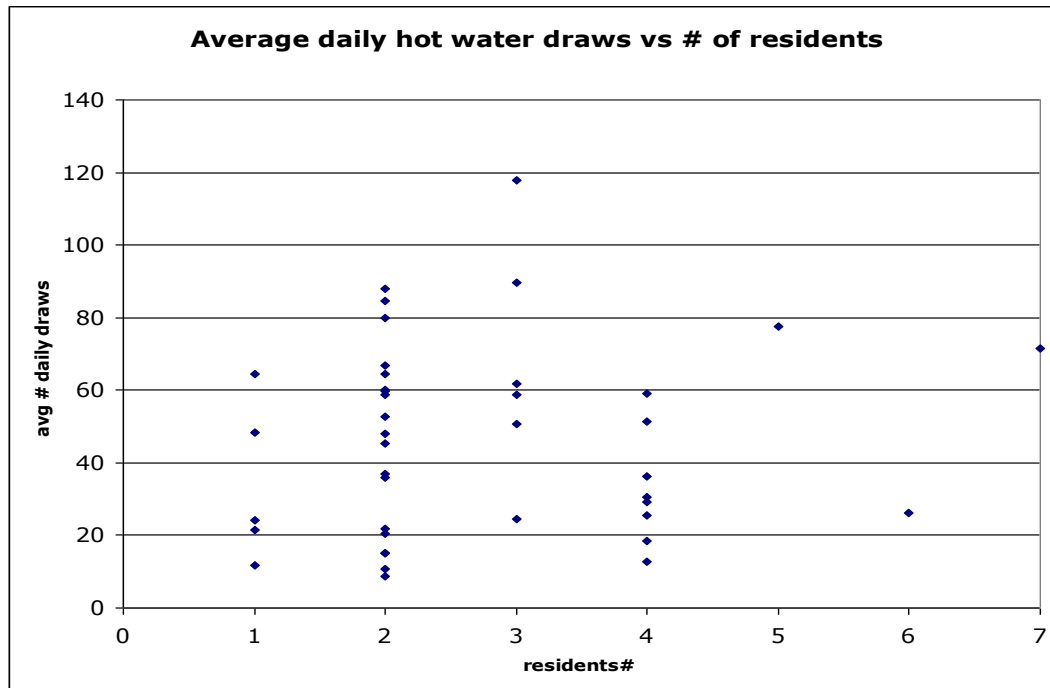


Figure 3. Average Daily Draws by Number of Residents

Figure 4 shows the average temporal distribution of hot water draws over a 24-hour period on all days for all of the sample houses. It shows a somewhat different pattern than the one for hot water volume, as there is a large number of lower-volume draws around dinner time.

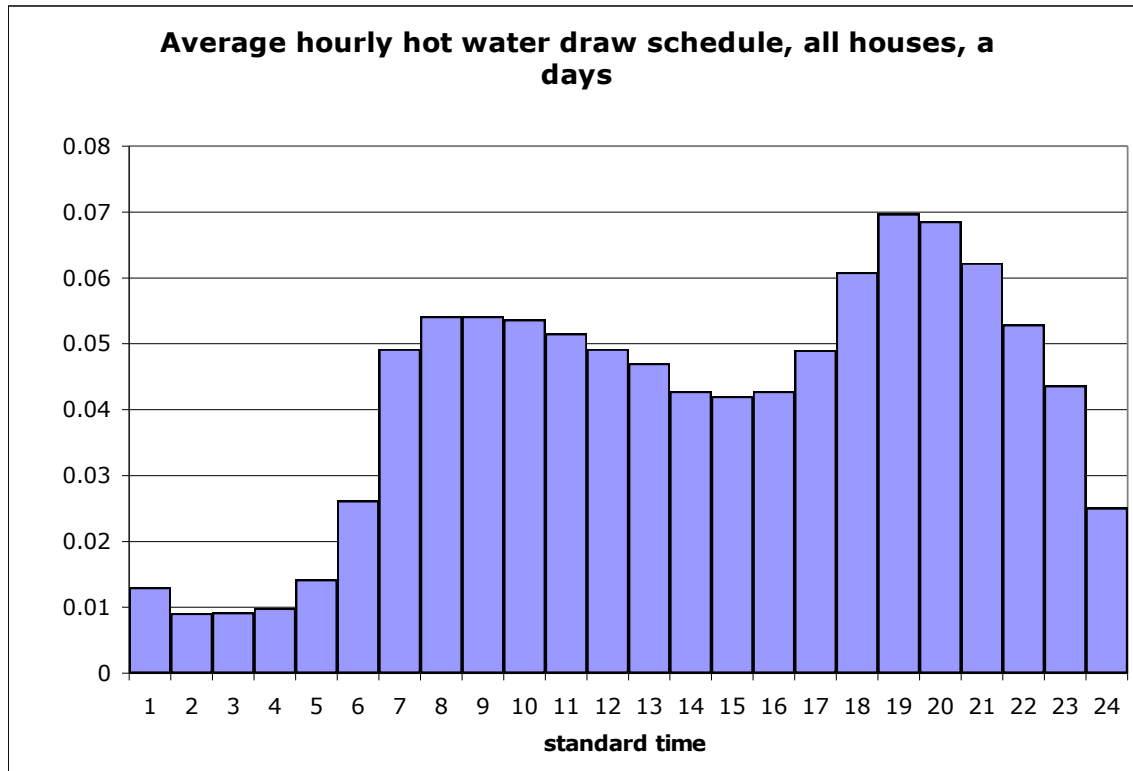


Figure 4. Average Number of Draws by Hour of Day

Figure 5 shows that there is a fairly good correlation between the average daily volume and the average daily number of draws. On average, the homes in this sample used 1.37 gallons per draw.

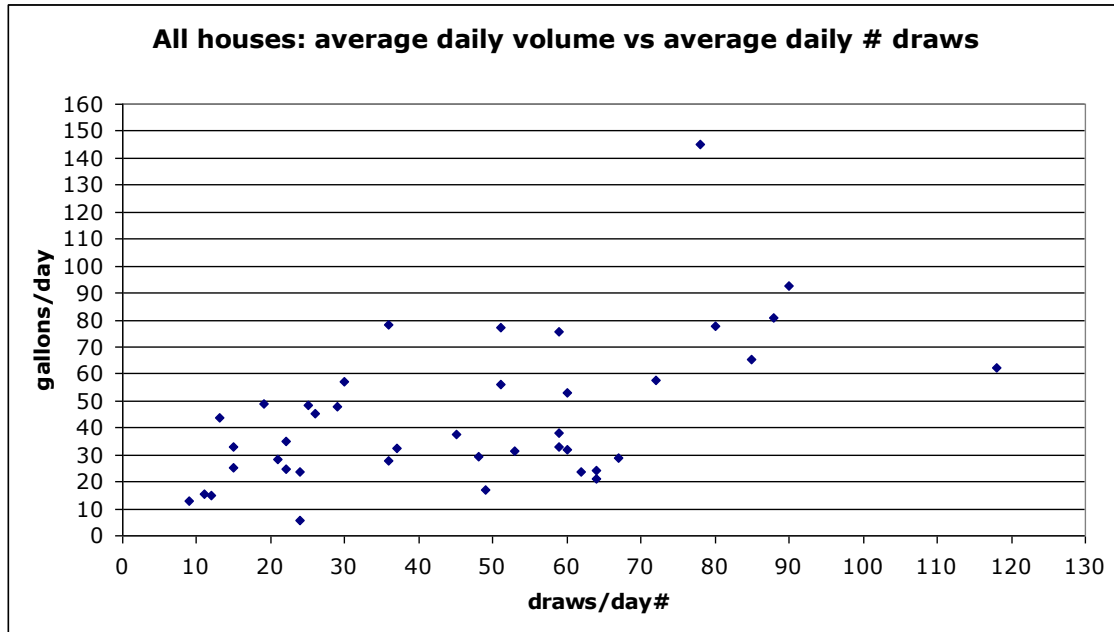


Figure 5. Average Daily Volume by Number of Draws

Water and Wastewater Tariff Report

This report is based on tariff information for 41 providers of both water and waste water services, 21 providers of water services only, and 13 providers of waste water services only. The total is 75 companies or governmental agencies, of which 62 provide water service and 54 provide waste water service.

Nearly all of the water tariffs in our sample also include a quantity charge based on metered water consumption. In California, it has been a requirement since 1992 that all new construction include a water meter. Since that law went into effect, most water providers have chosen to base tariffs on water consumption, but a few have not. In our sample, we found that only 4 out of 62 water service providers (6%) have flat rates for new residences. The largest of these is the City of Sacramento, which is on record as opposing metered water rates.

For those tariffs which have rates based on water consumption, we determined what the marginal rate would be for the 11th hundred cubic feet (HCF) consumed in a month (10 HCF per month is a typical quantity for residential water consumption). Since each utility might have several tariffs based on meter size, but with the same marginal rate, for each utility we identified the unique marginal rates. For 4 utilities, the value was \$0, because even though those utilities do have a water consumption charge, there is a certain amount of water usage that is included in the monthly fixed fee, and the 11th HCF fell below this amount. Of the non-zero values, the lowest was \$0.24/HCF, and the highest was \$5.28/HCF. This high value was for a utility which has what we refer to as a “disappearing” block structure, i.e. the lower rate for the first 0 to 10 HCF is lost if an 11th HCF is consumed, so the effective rate for the 11th HCF is the rate for that HCF plus the additional charge that is incurred on HCF 0 to 10. The unweighted average value for the 11th HCF, including the zeroes for flat rate tariffs, was \$1.40.

The average of the non-zero values was \$1.52/HCF. Figure 6 shows the distribution of charges for the unique tariffs.

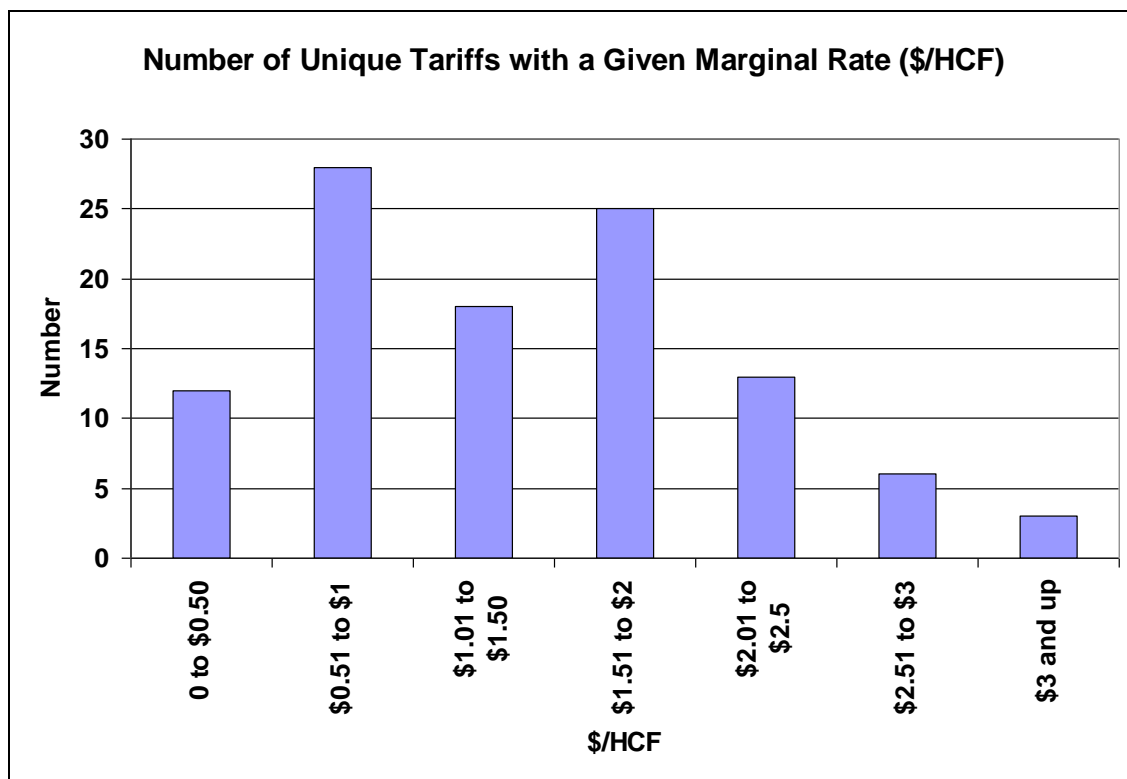


Figure 6. Number of Tariffs by Marginal Rate

For waste water, we found that 41 out of 54 service providers (76% of our sample) have flat rates that are completely independent of water consumption. Of the remaining 13 there are 6 who base their rates on metered water consumption during a base period in the previous winter – the rates are fixed for a year based on the last year’s water consumption and then adjusted once a year. The remaining 7 base their rates on each month’s metered water consumption. Sometimes the utilities apply an additional multiplier to estimate what fraction of water use (whether it’s winter water use or monthly metered water) is released to the sewer (typically 75% to 90%). For those utilities that apply such a multiplier, we multiplied the nominal rate per HCF times this multiplier to calculate the actual charge per metered HCF, and entered the actual charge into our database. For example, if a utility has a nominal sewer charge of \$2.00/HCF, and multiplies 90% times metered water use to estimate sewer use, we multiplied \$2.00 times 90% and entered \$1.80/HCF into our database, since this is the effective charge per HCF of metered water use.

Of the 13 companies that base sewer rates on water use, there were 2 that only based it loosely on water consumption within broad categories. For example, a city might charge \$10/month for users whose estimated sewer use is 0 to 5 HCF, \$15/month for 6 to 10 HCF, and \$20/month for 11 or more HCF. We modeled this in the database by counting the \$10 charge for the lowest

usage category as a fixed monthly cost (since all users pay at least this amount). We entered consumption charges of \$0/HCF for the first 5 HCF, \$5/HCF for the 6th HCF (this is the additional cost incurred by the 6th HCF since it bumps the user up into the next category), \$0 for the 7th through 10th HCF, \$5 for the 11th HCF, and \$0 for all additional HCF.

There were 17 unique tariffs for the 13 companies which have consumption charges (4 companies had different rates for multifamily residences than for single family). We calculated the charge for the 11th HCF consumed in a month. There were 4 tariffs out of 17 where the marginal rate was \$0. The lowest non-zero value was \$0.47/HCF, the highest was \$11.54/HCF. The highest value was from one of the two that bases its rates on categories of consumption, as described above. The 11th HCF is the transition from one category to the next highest, thus the marginal cost for that one HCF is quite high.

The average marginal cost per HCF of waste water, including zeroes for all 41 of the flat rate utilities, was \$0.74/HCF. The average of the non-zero values was \$3.23/HCF.

Ground Heat Transfer Algorithm Report

Many published heat transfer algorithms and models for application to generalized problems, hot water distribution systems, ground-source heat pumps and ground heat exchangers, nuclear waste repositories, buried oil pipelines, and underground electricity transmission cables could be adapted to the analysis of under-slab hot water piping.

Many factors affect the thermal efficiency of under-slab hot water distribution piping. The factors that should be accounted for in a rigorous system model are summarized below.

- The hot water temperature, thermal conductivity, density, specific heat, and flow rate are important parameters in any distribution system model. Variations in the thermal properties with temperature must be considered.
- Copper, polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), high-density polyethylene (HDPE), polypropylene, and polybutylene can be used for under-slab hot water distribution piping. Various types of insulation can be placed around the piping. Thermal conductivity, density, and specific heat values of the piping and insulation, and their variations as functions of temperature, if significant, are important model inputs.
- Piping length, wall thickness, and friction factor affect distribution system efficiency. Typical under-slab hot water piping has short vertical lengths at the inlet and outlet locations, and a much longer horizontal length between them. Although it is tempting to disregard the short inlet and outlet segments to simplify a model, these components are important because of the heat losses and resistances to fluid flow that they comprise.
- Fine gravel, sand, cementitious grout, clay, and loam can be used as backfill around the hot water piping and directly under the slab. The thermal properties of the backfill materials in both of these locations, as well as those of the concrete slab and surrounding soil, must be taken into account. The base temperatures of these materials vary with time of year, and their properties vary with moisture content. Additionally, the model must consider the presence and migration of groundwater, which dramatically affects the thermal properties of soil. The model must also treat the vertical asymmetry of the

materials involved; in particular, it must incorporate the thermal reservoir effect of the soil or ground below the piping and the convective pool of the large air space above the slab.

- Hot water, unlike heating, cooling, and ventilation, demand derives from multiple end uses. Consequently, it exhibits complex temporal variations—hourly, daily, seasonal, etc. The resulting water draw patterns drive cyclical, sporadic, and transient piping heat losses that must be characterized accurately to determine distribution system efficiency for any time interval of interest. The most useful model will be one that permits wide variability in the calculational time step.
- The heated water remaining in the piping after a given hot water draw event is left to reach thermal equilibrium with its surroundings. Depending on the water temperature, piping, backfill, slab, and soil properties and configuration, and timing of the next draw event, this equilibrium might or might not be reached. Thus, the temperature of the residual water encountered by the next flux of hot water is highly variable. To further complicate the model requirements, any one of the following interactions between the next flux of hot water and the residual water might occur: (1) the hot water might drive the residual water through the piping ahead of it; (2) the hot water might mix with the residual water; or (3) the hot water might flow over the residual water, with accompanying conductive and convective heat exchange. Furthermore, due to the combined influences of all variables under consideration, this interaction might be different for each time step (draw event).

As suggested by many authors, the thermal properties of inhomogeneous localized geological media are important in ground-coupled building system models but are difficult to obtain or determine. Without adequate data of this type, an under-slab hot water piping model will suffer from inaccuracy.

Instantaneous Gas Water Heater LDEF Report (Field and Laboratory Testing of Tankless Gas Water Heater Performance)

Instantaneous, or tankless gas water heaters have the potential to significantly improve residential water heating energy efficiency due to higher combustion efficiencies and the elimination of the standby losses common to gas storage water heaters. In the last decade a new breed of instantaneous gas water heaters with Energy Factors of 0.80 or higher have been introduced to the market, considerably higher than the typical 0.60 Energy Factor for gas storage water heaters. These newer tankless models represent a significant improvement over units of twenty to thirty years ago as a result of both eliminating standing pilots and by integrating sophisticated controls that vary burner capacity to meet supply water setpoints under varying flow rates. Eliminating the standby heat loss results in a significant efficiency advantage that increases as hot water loads decrease.

Both tankless and storage gas water heaters are tested under procedures defined by the U.S. Department of Energy. The Energy Factor testing procedure prescribes six equal hot water draws (totaling 64.3 gallons) at one-hour intervals. The remainder of the 24-hour test period is used to account for standby losses. Although storage water heaters are not significantly affected by the hot water draw profile, tankless units experience greater sensitivity to the number and frequency of draws since the heat exchanger must be raised to temperature for each draw event.

The primary goal of this study was to assess the performance implications of hot water draw patterns on tankless gas water heater performance. Data collected from an occupied house currently being monitored under the Building America program was used to document field performance of a tankless gas water heater. In addition, a second tankless unit was tested at Davis Energy Group's shop facility to support field findings and facilitate data collection under more controlled conditions.

The Building America monitoring effort was directed towards comparing performance of a conventional storage gas water heater to a tankless unit. Figure 7 plots initial data comparing the daily efficiency for both the storage water heater and the instantaneous unit. Clearly the storage gas water heater performance is impacted to a greater degree at low daily hot water draw volumes as the standby loss represents an increasingly larger fraction of the total energy consumed. The instantaneous unit also demonstrated some performance degradation at low draw volumes, presumably due to increased cycling.

With these preliminary results, Davis Energy Group decided to install the 20 pulse/ft³ gas meter to increase data resolution at smaller draw volumes. Figure 8 plots the calculated efficiency as a function of the volume of each individual draw during this period. The data demonstrate a sharp drop off in efficiency at draw volumes under 4 or 5 gallons. There is also significant scatter, especially as the hot water draw volumes approach zero. One factor affecting the scatter remains the resolution of the gas meter. Even at a high resolution rate of 20 pulses per cubic foot (~50 Btu/pulse), any one draw could potentially over or underestimate gas consumption by a maximum of two pulses (one pulse at each end of the draw). For a two gallon hot water draw with a 60°F hot to cold water temperature difference, a 100 Btu inaccuracy could affect the calculated efficiency by as much as $\pm 6\%$. The second factor is the time interval between hot water draws. For draws with just a few seconds between firing cycles, the impact on efficiency of heat exchanger "cool down" is insignificant since the heat exchanger is close to operating temperature. However as the time between draws increases, more of the initial firing energy is needed to bring the heat exchanger up to temperature. The impact of this initial firing energy becomes insignificant in large draws (> 10 gallons) where the warm up energy is negligible related to the total energy delivered.

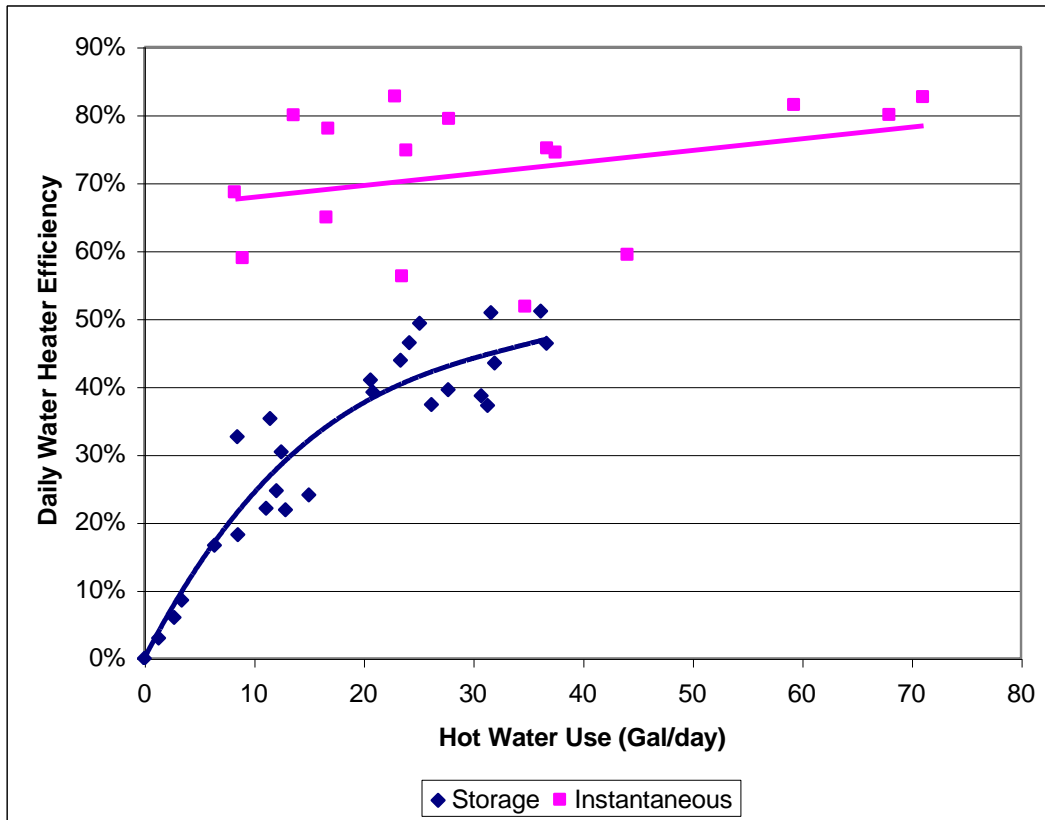


Figure 7. Comparison of Daily Water Heater Efficiency

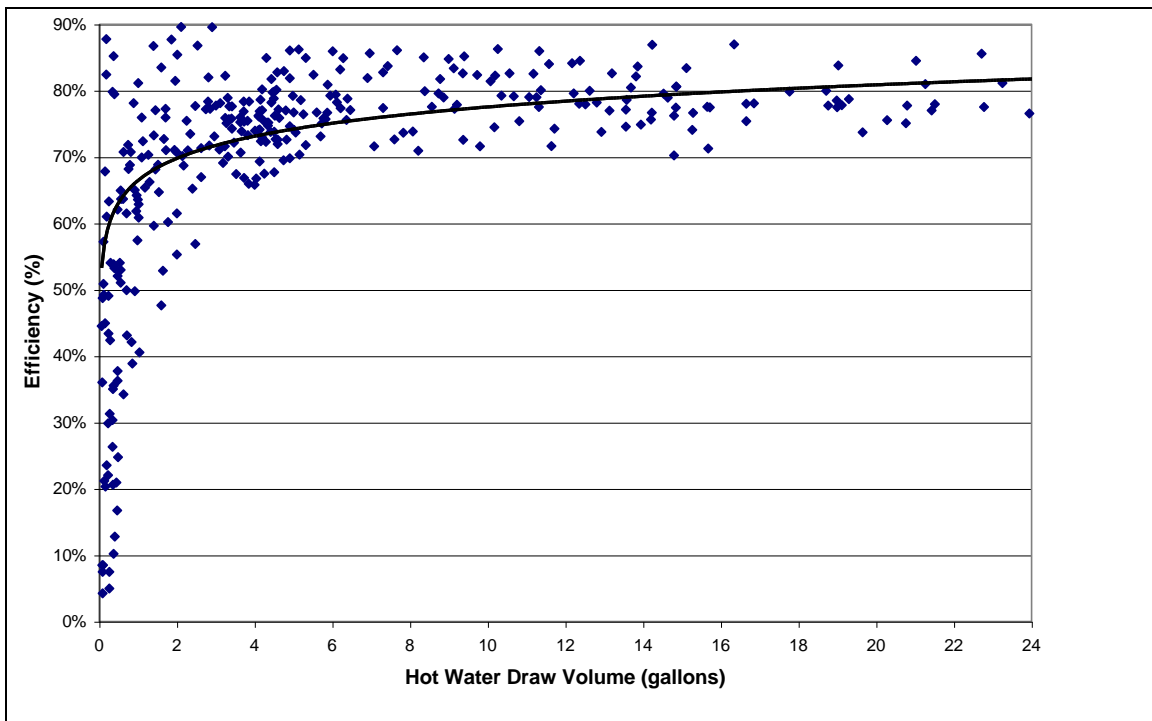


Figure 8. Monitored Field Efficiency of Tankless Water Heater

In addition to the field testing, further monitoring was completed at the Davis Energy Group shop on the Takagi T-K Jr. to better understand performance degradation at low draw volumes with varying flow rates and time intervals between draws. Figure 9 plots data from a series of tests with varying flow rates (1.2 to 2.3 GPM) and varying time intervals between hot water draws (5 and 45 minutes) at the default factory temperature setting of 122°F. The data demonstrate a relationship similar to that shown for the field measurements, but Figure 9 more clearly depicts the impact of cool down time on system efficiency. The “5 minutes between draw” tests show an ~ 10-15 percentage point drop in efficiency at draw volumes of 1 gallon (relative to 10 – 15 gallons), while the “45 minutes between draws” show a much more significant drop. This efficiency disparity is largest at small volumes and approaches zero at about 4 gallon draw volumes. The impact of flow rate appears to be negligible for the “5 minute” data, although the “45 minute” interval data does demonstrate some variation due to flow rate. This is largely due to the effect of the lower flow rate allowing more time for the heat exchanger to achieve temperature than at a higher flow rate.

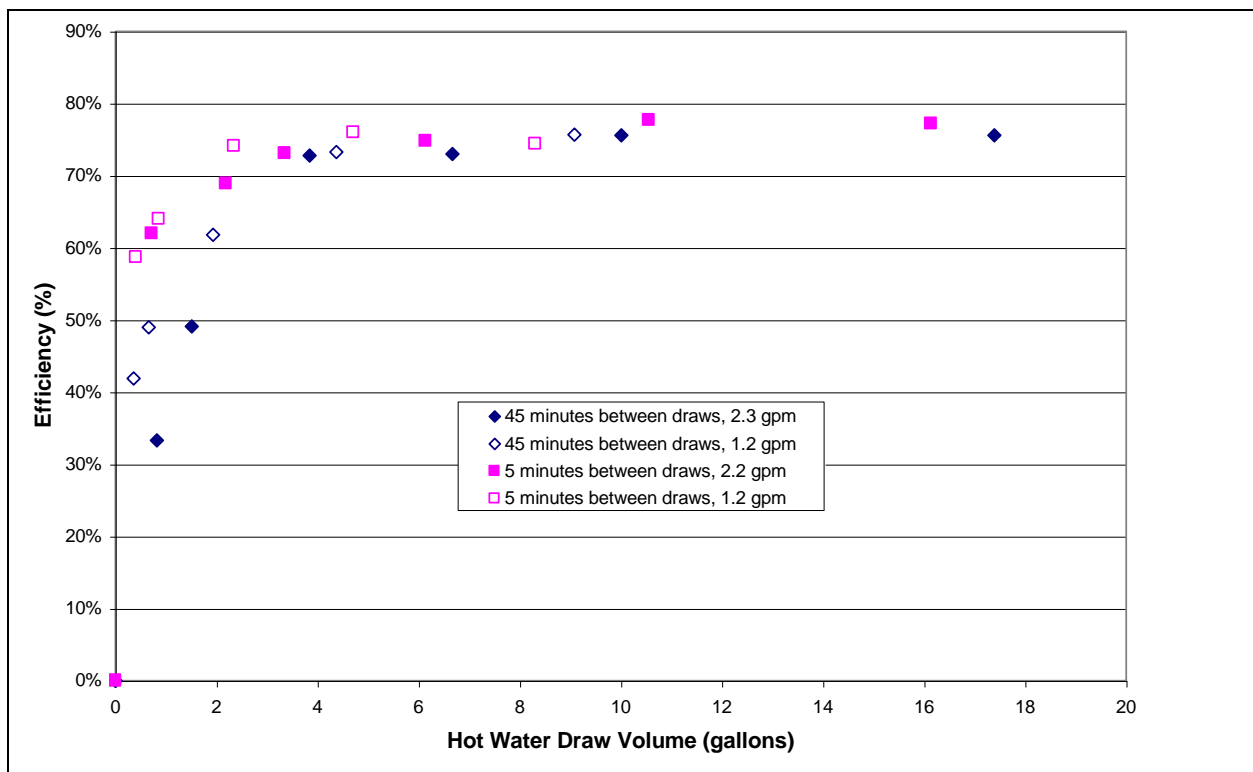


Figure 9. Monitored Lab Efficiency of Tankless Water Heater

Figure 10 presents a subset of the data shown in Figure 9 (hot water volumes less than five gallons), since this is the region where tankless performance is subject to the greatest degradation. For the zero to four gallon draw volume range we evaluate performance under

two cool down scenarios: 5 minute cool down and 45 minute cool down (at 2.3 GPM flow rate). Figure 9 shows a smoothed curve through the lab monitored data points. In addition vertical lines are shown at 0.5, 1.5, 2.5, and 3.5 gallons. A representative efficiency can be defined where the vertical lines intercept the curve. For example, at 0.5 gallons, efficiencies of 21% and 60% are estimated, for 45 and 5 minute intervals, respectively.

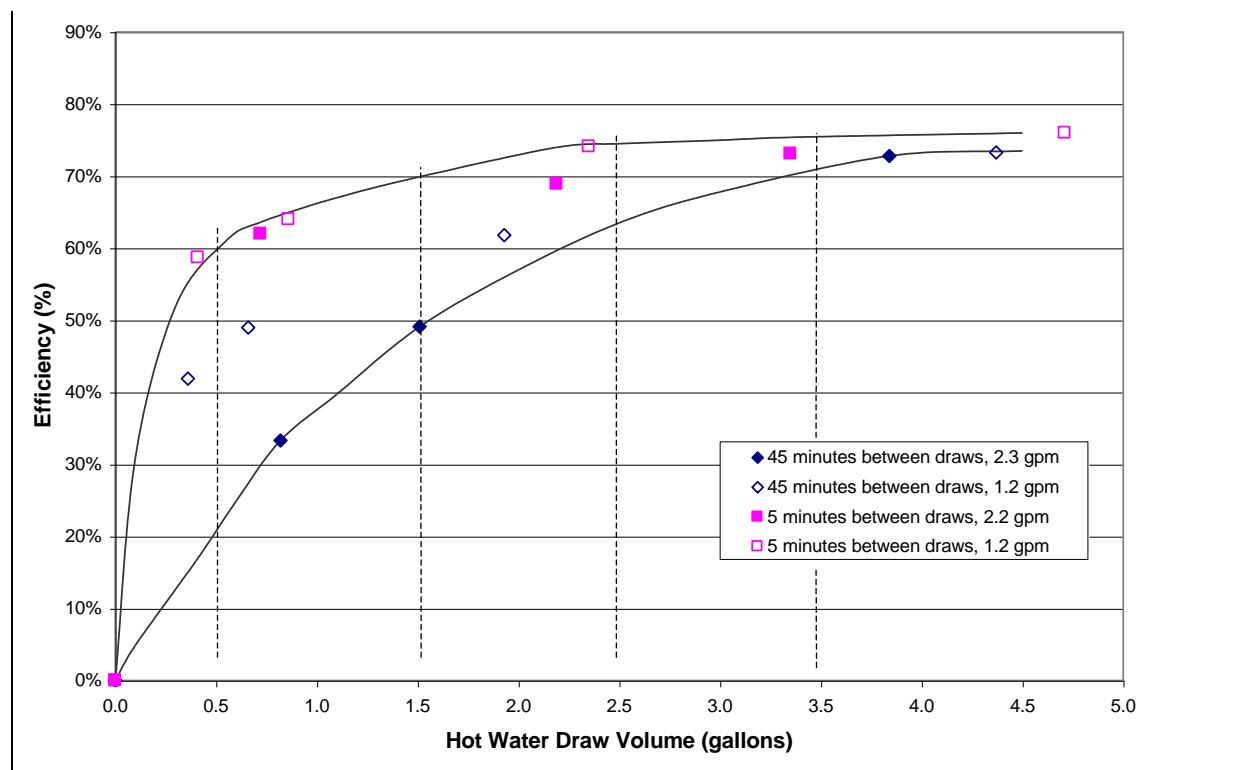


Figure 10. Efficiency as a Function of Volume and Time Between Draws

The final step in developing a realistic degradation term for tankless water heaters involves applying the efficiency curves to the assumed load profiles. Table 2 disaggregates the assumed hot water load into one gallon bins. The assumption is also made that at an eleven gallon hot water draw, the efficiency of a tankless unit is equal to the rated recovery efficiency, in this case 81.6%. Estimated efficiencies for draws of four gallons or less are based on Figure 9. From five through ten gallons, a linear relationship is assumed. As shown in Table 2, ~90% of the performance degradation occurs for draw volumes less than four gallons. This is due to the low efficiencies and fairly high usage at low volume, as well as the absence of degradation at large draws where 70% of the usage is assumed to occur.

The difference between hot (77.3%) and cold starts (70.3%) is fairly significant when compared the assumed nominal 81.6% efficiency.

Table 4. Projected Typical Tankless Performance (Cold and Hot Start)

Hot Water Draw Vol (gallons)	% of Total Load	"Cold Start"		"Hot Start"	
		Estimated Thermal Efficiency	Weighted Efficiency	Estimated Thermal Efficiency	Weighted Efficiency
1	9.0%	21.0%	1.9%	60.0%	5.4%
2	10.0%	49.0%	4.9%	70.0%	7.0%
3	7.0%	63.0%	4.4%	74.0%	5.2%
4	5.0%	71.0%	3.6%	76.0%	3.8%
5	2.0%	72.5%	1.5%	76.8%	1.5%
6	2.0%	74.0%	1.5%	77.6%	1.6%
7	1.0%	75.5%	0.8%	78.4%	0.8%
8	4.0%	77.1%	3.1%	79.2%	3.2%
9	5.0%	78.6%	3.9%	80.0%	4.0%
10	5.0%	80.1%	4.0%	80.8%	4.0%
11	6.0%	81.6%	4.9%	81.6%	4.9%
12	8.0%	81.6%	6.5%	81.6%	6.5%
13	8.0%	81.6%	6.5%	81.6%	6.5%
14	8.0%	81.6%	6.5%	81.6%	6.5%
15	5.0%	81.6%	4.1%	81.6%	4.1%
16	4.0%	81.6%	3.3%	81.6%	3.3%
17	3.0%	81.6%	2.4%	81.6%	2.4%
18	3.0%	81.6%	2.4%	81.6%	2.4%
19	3.0%	81.6%	2.4%	81.6%	2.4%
20	2.0%	81.6%	1.6%	81.6%	1.6%
Overall Efficiency			70.3%		77.3%

HWDS Pressure Loss Report

For the six houses studied ORNL found that pressure loss due to friction and vertical rise was not the determining factor in whether incrementally smaller diameter systems would be acceptable. Excessive hot water velocity occurred before pressure loss in a particular smaller system became a limiting factor. Some of the incrementally smaller systems exceeded the generally accepted 5 ft/sec maximum hot water velocity for copper pipe and 10 ft/sec overall code maximum. Limiting velocity is used to reduce the erosive corrosion on both copper and plastic pipes, and, to a lesser degree, to reduce the noise.

The study calculated the friction loss of the plumbing pipes at about 30% of the total loss the remaining 70% was due to vertical rise. Using the Bernoulli's equation, with the assumption of the hot water pipe total loss, including rises and friction losses, 25 PSI inlet water pressure is more than enough to provide needed volume of hot water, if the total loss is not excessive.

Because CPVC pipes, with the same nominal sizes as that of copper pipes, have larger inside diameters, they can have higher flow rates and yet still remain within the maximum hot water

velocity allowed. On the other hand PEX of the same nominal size has smaller interior diameter than both CPVC and copper and thus the velocity is higher for a given flow.

Table 5 details the full range of velocities for the various pipe materials and sizes. From it we can see that reducing the branch serving a lavatory/sink (1.5 GPM) to 3/8" is acceptable for all materials. For a shower (2.5 GPM) the branch could also be reduced to 3/8" if CPVC or PEX were utilized. For flows of 4.0 GPM (some mains) a 1/2" line is adequate if CPVC or PEX were used. For mains with a flow rate of 6.5 GPM a 1/2" CPVC pipe is also adequate.

Table 5. Hot water flow velocity for Copper, CPVC, and PEX pipes

Nom Size	Max. Velocity, ft/sec											
	1.5 GPM			2.5 GPM			4.0 GPM			6.5 GPM		
	Copper	CPVC	PEX	Copper	CPVC	PEX	Copper	CPVC	PEX	Copper	CPVC	PEX
1"	0.62	0.56	0.82	1.03	0.93	1.37	1.65	1.48	2.19	2.68	2.41	3.57
3/4"	1.10	0.90	1.32	1.84	1.51	2.20	2.94	2.41	3.52	4.79	3.91	5.73
1/2"	2.21	1.58	2.72	3.68	2.64	4.53	5.88	4.22	7.24	9.56	6.87	11.77
3/8"	3.79	2.52	5.00	6.32	4.20	8.34	10.11	6.72	13.34	16.43	10.92	21.68
1/4"	6.59	4.63	12.11	10.98	7.71	20.17	17.57	12.33	32.28	28.55	20.04	52.46

Notes:

Red indicates the velocity is over the 5 ft/sec for copper and 10ft/sec for CPVC and PEX pipes.

Because CPVC pipes, with the same nominal sizes as that of copper pipes, have larger inside diameters, they can have higher flow rates and yet still within the maximum hot water velocity allowed.

These potential pipe size reductions may appear small, but they would reduce the entrained hot water volume by approximately 40%. This reduction would proportionately speed the arrival of hot water to the end use fixture as well as reduce the volume of water to be wasted awaiting the arrival of hot water.

3.1.5. Validate HWDS Simulation Models

HWSIM Program Development Overview

HWSIM is a first principles model that tracks the flow of water from the water heater¹ through the user-defined piping system to each hot water end-use point. HWSIM tracks the thermal interactions of the water in the pipe as it flows through various piping materials (with or without insulation) and through various environments with surrounding temperatures that can change monthly and/or hourly. Pipe sections are broken into 0.01 gallon (typical) volume

¹ Hot water leaves the water heater at a fixed outlet temperature (no tank temperature variations are assumed).

elements to analyze water-to-pipe and pipe-to-environment heat transfers. Turbulent conditions are assumed for water-to-pipe heat transfer and horizontal still-air is assumed for pipe-to-air heat transfer for each element.

The user schedules a set of draws for each use point consisting of the hot water flow rate, water volume, the type of draw, the minimum water temperature required, and the initial ratio of hot to cold water use at the fixture². The draw type can be one of three: Appliance draws are assumed to consume 100% hot water; MixedTemp draws use a volume of water, such as a tub, at a final desired mixed temperature; and MinTemp draws, such as a shower or sink, require a specified minimum hot water temperature before the “useful” hot water draw begins. MinTemp draws waste flowing water until the minimum use temperature is achieved. At the completion of a draw, the piping system sits static until either the end of the hour or until the next draw occurs, whichever comes first. At that time, HWSIM performs a thermal decay calculation to update the combined water/pipe temperature based on the initial temperature of the volume element, the pipe heat loss characteristics, the local environment temperature for that element, and the time since the end of the last draw.

The user provides a plumbing layout, as well as a schedule of hot water draws. The program tracks:

- Energy flows (leaving the water heater, leaving the use point, pipe losses)
- Hot and cold water used
- Hot and cold water wasted (for MinTemp draws before minimum use temperature is achieved)
- Distribution system efficiency
- Water use efficiency
- Water heater efficiency

Validation Results

A series of validation graphs follow in this section. The validation effort focused on determining proper adjustment factors for h_o , h_i , and the “ q_{mix} ” term. The “ h ” factors represent direct multipliers on the heat transfer coefficients calculated by HWSIM. The q_{mix} term was added in an effort to mimic the slip flow phenomena observed by AET in the lab. The q_{mix} term is basically a U-value between adjacent volume elements (typically 0.01 gallons) within a pipe. The greater the q_{mix} term, the greater the thermal transfer down the pipe in advance of the flowing plug of hot water.

Figure 11 plots outlet hot water temperature data for 100 feet of ½” copper in 67.5°F air at varying hot water flow rates. The graph plots AET lab data and HWSIM results for h_o , h_i , and q_{mix} values of “1.0, 1.0, 1.0” (unadjusted) and “1.3, 1.0, 1.0”. The latter case was found to match nearly exactly for this case and also matched well for ¾” copper.

2 Hot water ratio accounts for single lever fixtures where the initial position dictates the ratio of hot water flow to total flow with resulting impact on water wasted before desired temperature is reached.

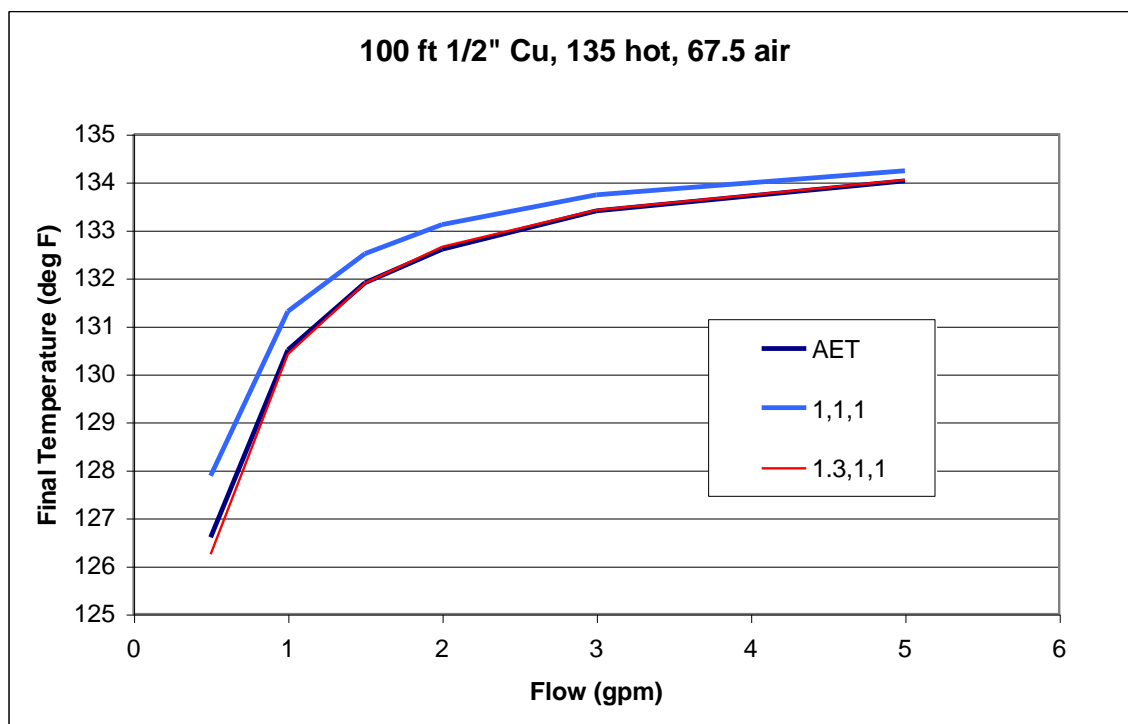


Figure 11. Pipe Heat Transfer Coefficient Impact

Figure 12 plots outlet temperature vs. flow rate for $\frac{1}{2}$ " and $\frac{3}{4}$ " copper in air, and $\frac{1}{2}$ " copper with $\frac{1}{2}$ " insulation in air. These plots use the "1.3,1.0,1.0" set of factors. The two uninsulated cases show very good agreement over the full flow rate range. The insulated case shows small divergence, particularly at the very low 0.5 gpm flow rate. Since the uninsulated case provides a good match, the small deviation is likely due to the conductivity specification or the model assumption of perfect insulation performance vs. the small anomalies that can't be avoided in the laboratory. Figure 3 shows a similar plot for $\frac{3}{4}$ " PAX, in air and insulated. Again the uninsulated case shows very good alignment, with a greater divergence in the insulated case.

Figures 14-17 provide a comparison of AF/PV lab results to model predictions. In general the lab data shows a trend of decreasing AF/PV with both increasing flow rate and increasing pipe length. At the same time, the lab data shows variations that can be expected in doing experimental work; in other words trends are evident but not all data points follow the trend.

Figure 14 plots AF/PV data as a function of pipe length at a hot water flow rate of 0.49 gpm. HWSIM model results are shown for a range of h_i and q_{mix} values, with h_o fixed at 1.3. The HWSIM "1.3,1.0,1.0" and "1.3,1.0,0.0" lines sit directly on top of each other in this example. Given the small sensitivity to variations in the h_i and q_{mix} values, the recommended specification of "1.3,1.0,0.0" is proposed.

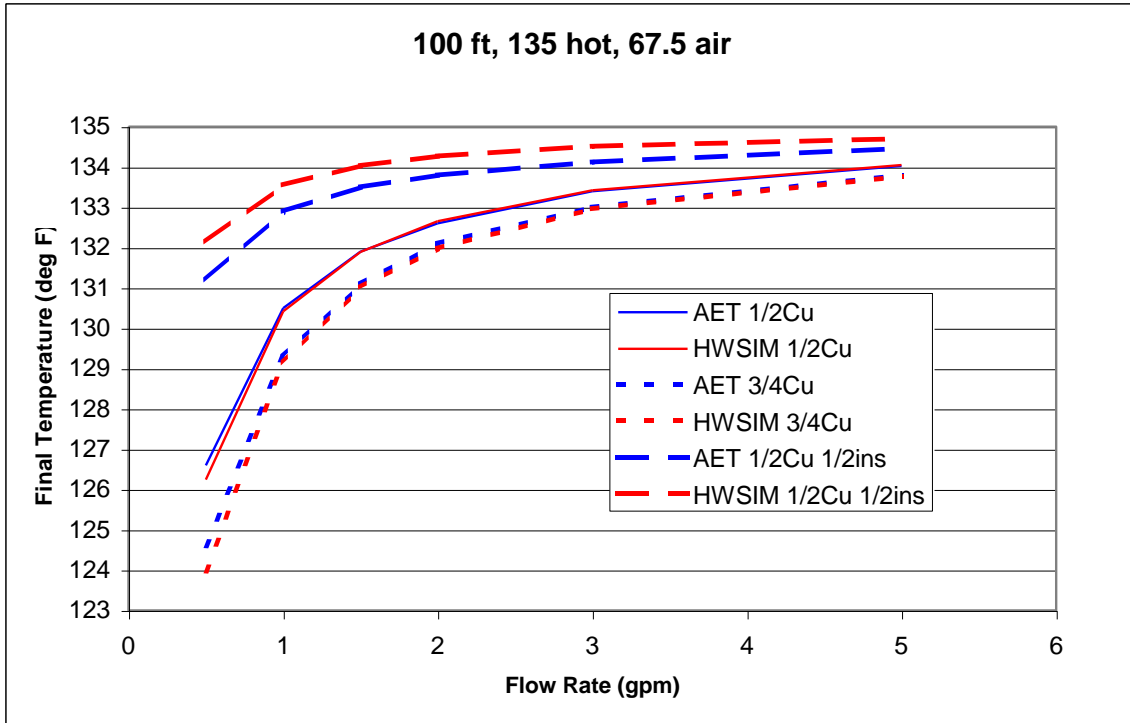


Figure 12. Model vs Lab Outlet Temperature Data (1/2" Cu, 3/4" Cu, 1/2" Insulated Cu)

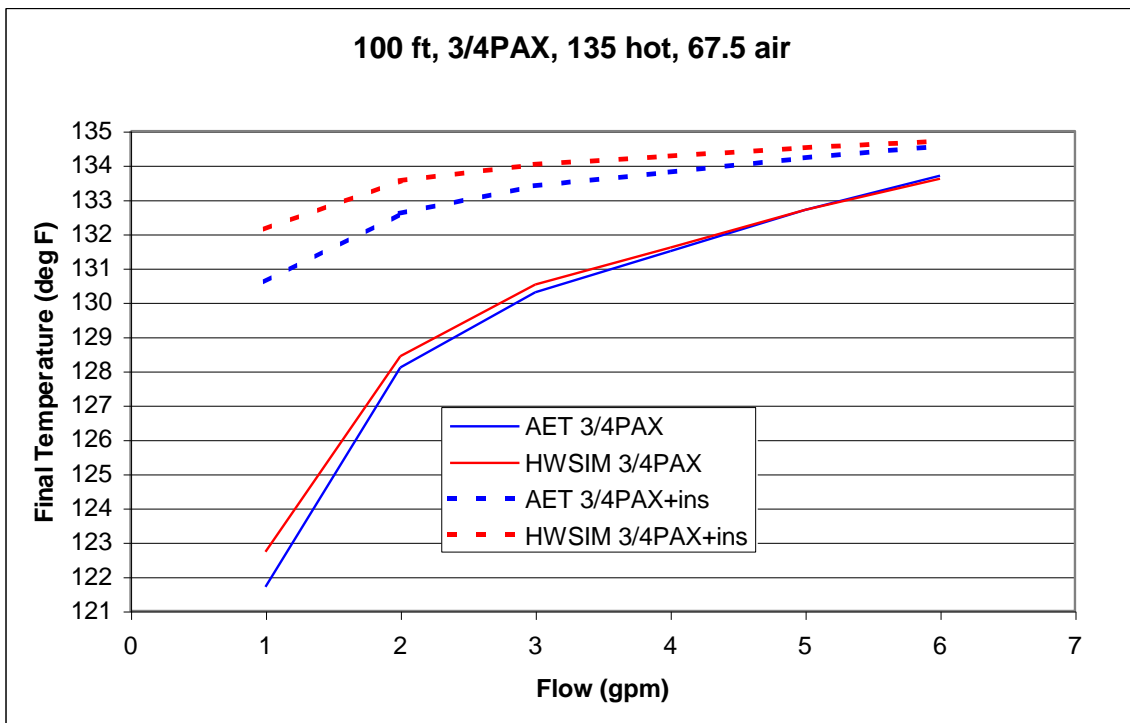


Figure 13. Model vs Lab Outlet Temperature Data (3/4" PAX, 3/4" Insulated PAX)

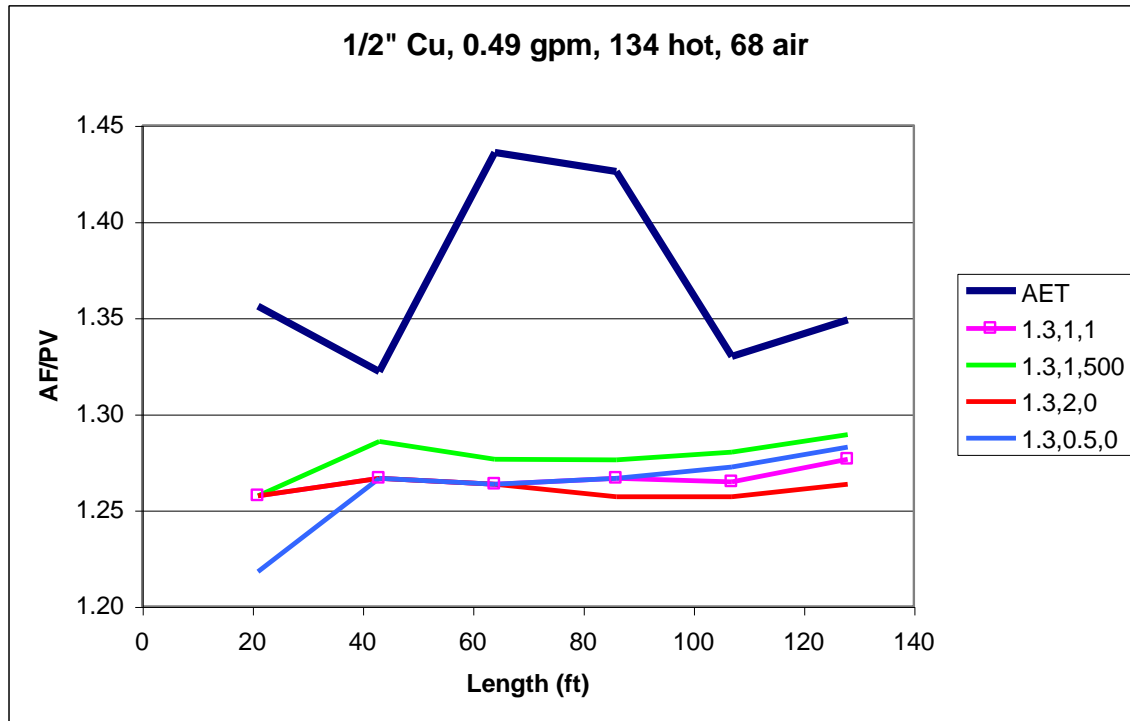


Figure 14. Model vs. Lab AF/PV Validation as a Function of Pipe Length (1/2" Cu)

Figure 15 takes this validation assumption and applies it to 135°F inlet hot water in 1/2" copper pipe in 65°F air. Four lab cases ("AET") are compared to four HWSIM projections at hot water flow rates of 0.49, 0.94, 1.6, and 3.02 gpm. Although the lab data shows a much greater AF/PV sensitivity to flow rate than the model, most residential hot water flow rates will occur in the 0.9 to 2.0 GPM range where the model matches the lab data quite well.

Figure 16 plots results for 120°F inlet hot water in 1/2" copper pipe in 70°F air. The lab data shows a stronger downward trend in AF/PV with increasing pipe length than HWSIM indicates. Similar to the Figure 5 data, outside of the low 0.49 GPM case, the model predictions are reasonably close to the AET lab results.

Figure 17 plots results for 135°F inlet hot water in 3/4" copper pipe in 58°F air. The lab data shows a similar trend to Figure 6, with generally higher AF/PV's for short lengths and a trend towards lower values for longer pipe lengths. HWSIM shows minimal variation with length, but on average matches well with the lab data at flow rates of 1.98 GPM and above.

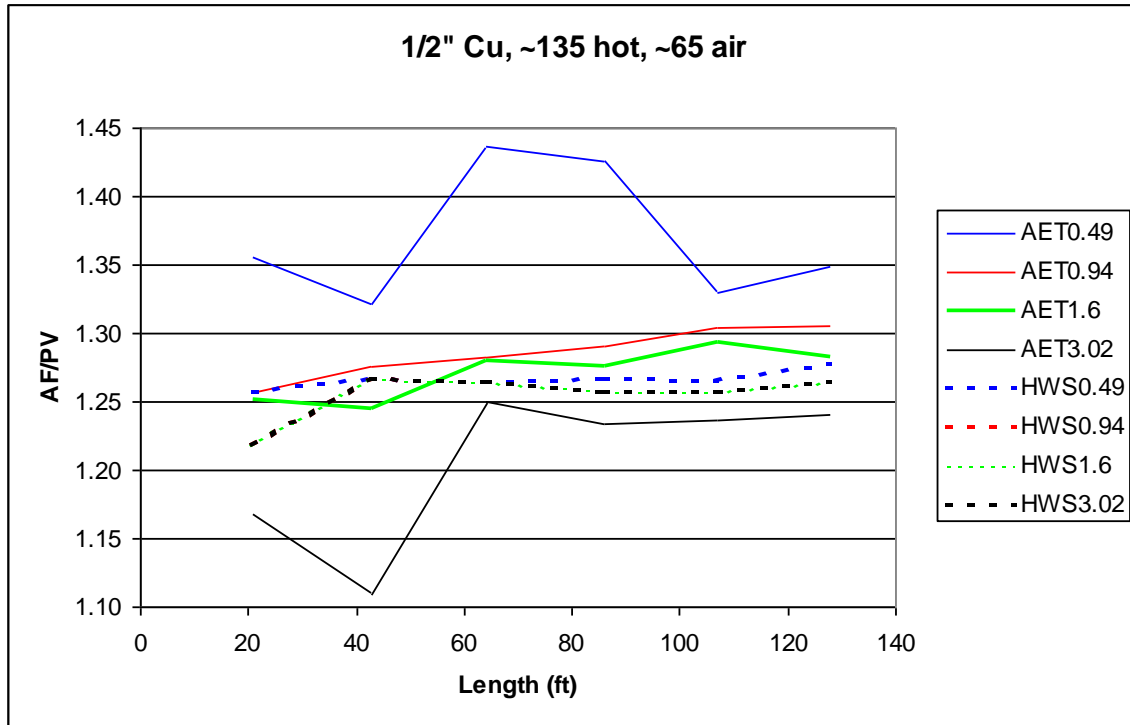


Figure 15. Model vs Lab AF/PV as a Function of Pipe Length & Flow Rate (1/2" Cu)

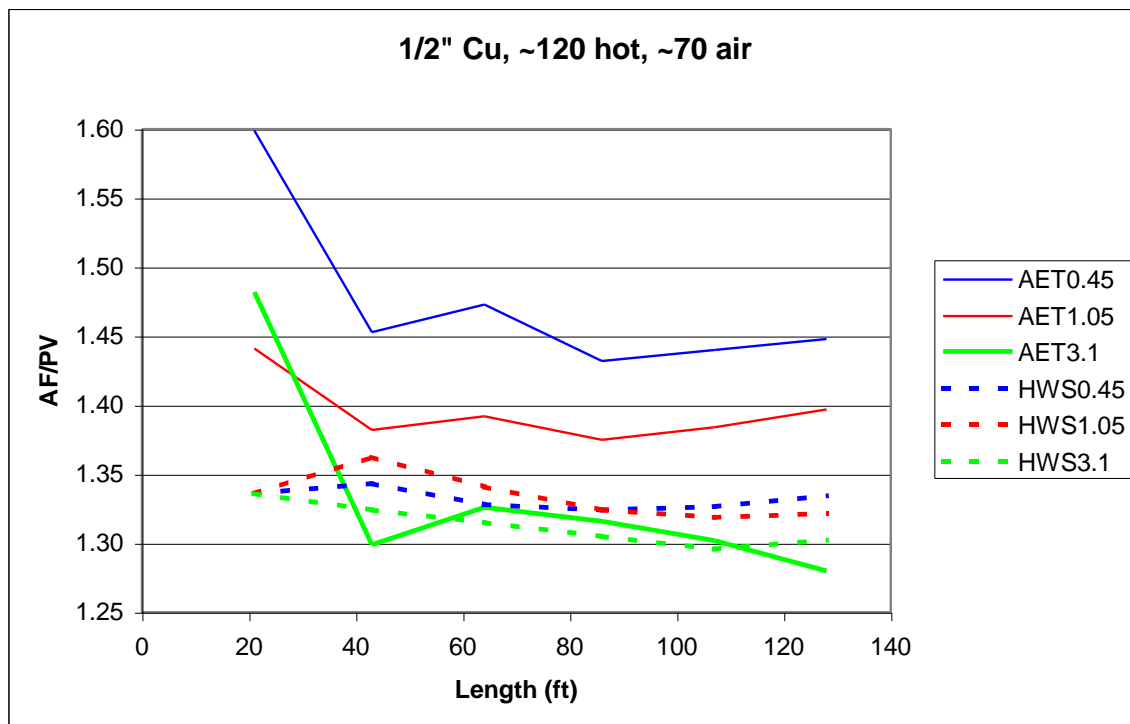


Figure 16. Model vs Lab AF/PV as a Function of Pipe Length & Flow Rate (1/2" Cu)

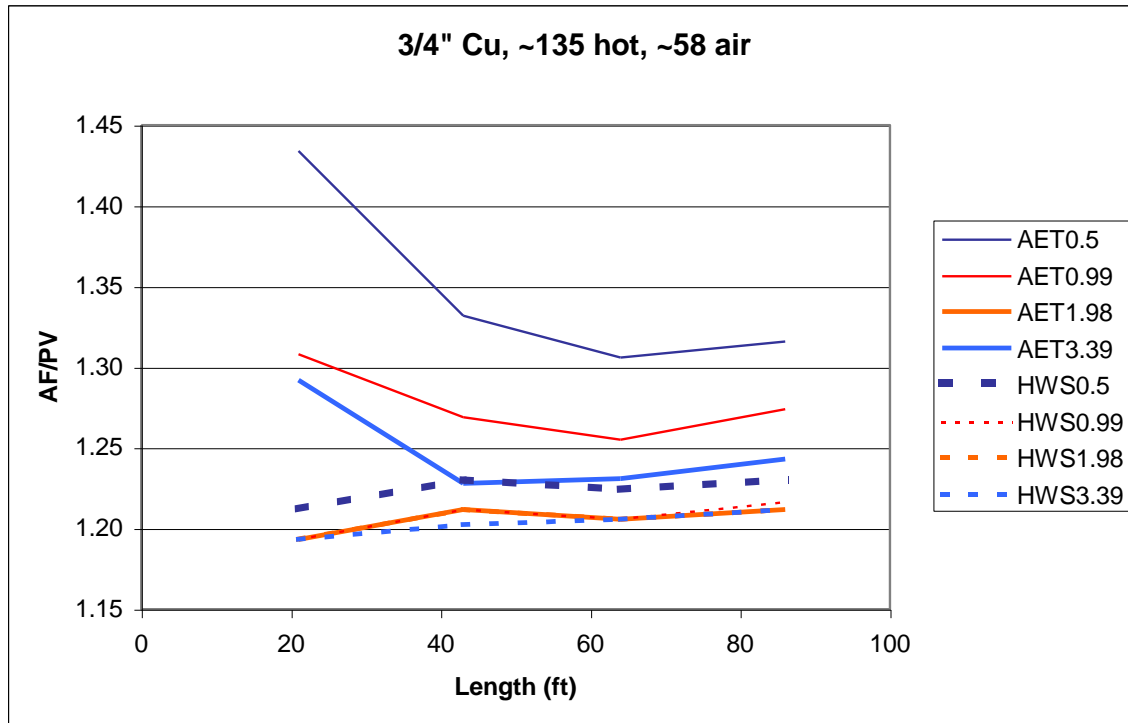


Figure 17. Model vs Lab AF/PV as a Function of Pipe Length & Flow Rate (3/4\" Cu)

The final step in the validation process is to look at how the model predicts the cool down of pipes between hot water draws. AET completed lab testing on various pipe configurations and determined an average effective pipe UA during non-flow situations. These loss coefficients were then used to determine pipe cooldown times. Table 6 summarizes the in-air cooldown times for insulated and uninsulated pipes at 135 and 125°F starting temperatures. To mimic this test, an HWSIM model was set up for each of the pipe cases shown in Table 6. A short two foot pipe section from the water heater was modeled to insure that the outlet water temperature would be very close to the assumed 135°F (or 125°F) tank outlet temperature. A five-minute draw was imposed, at the end of which a time delay was imposed (19.8 minutes for the "1/2\" Rigid Cu, no insl\" case). A second draw then ensued, and the initial outlet water temperature was recorded.

Table 6. AET Pipe Cool-down Data (time in minutes to reach 105°F in 67.5°F air)

Pipe Description	135°F Starting Temperature	125°F Starting Temperature
1/2\" Rigid Cu, no insl	19.8	14.4
1/2\" Rigid Cu, 1/2\" insl	35.8	26.0
1/2\" Rigid Cu, 3/4\" insl	40.4	29.4
3/4\" Rigid Cu, no insl	22.7	16.5
3/4\" Rigid Cu, 1/2\" insl	59.8	43.5
3/4\" Rigid Cu, 3/4\" insl	64.0	46.5
3/4\" PAX, no insl	18.1	13.2
3/4\" PAX, 3/4\" insl	56.3	47.1

Figure 18 plots this initial water temperature for each of the cases in Table 6. The x-axis label characterizes the insulation (none, 1/2", or 3/4") as well as the pipe material. Ideally, the cases shown should all converge to 105°F for 100% consistency with the lab data. On average for the 125 and 135° starting temperatures, HWSIM over-predicts the lab results by 2.6 and 3.5°F, respectively³. Curiously the trend isn't consistent with uninsulated 1/2" Cu showing a faster predicted decay, and all other cases showing a slower decay. Three potential factors could be affecting the decay results:

- The decay calculations are based on a lumped capacitance assumption that combines the energy contained in the pipe and water into a single combined temperature.
- The assumption of a "still air" pipe exterior convection coefficient may or may not fully represent conditions in the lab. Small environment effects or radiant heat transfer can have a sizable impact on pipe heat loss, especially for uninsulated pipes.
- HWSIM assumes perfect insulation performance at a fixed insulation R-value of 3.97 per inch. Although pipe insulation is required to be tested and rated, discrepancies in product catalog specifications raise some uncertainties as to actual performance characteristics of individual products.

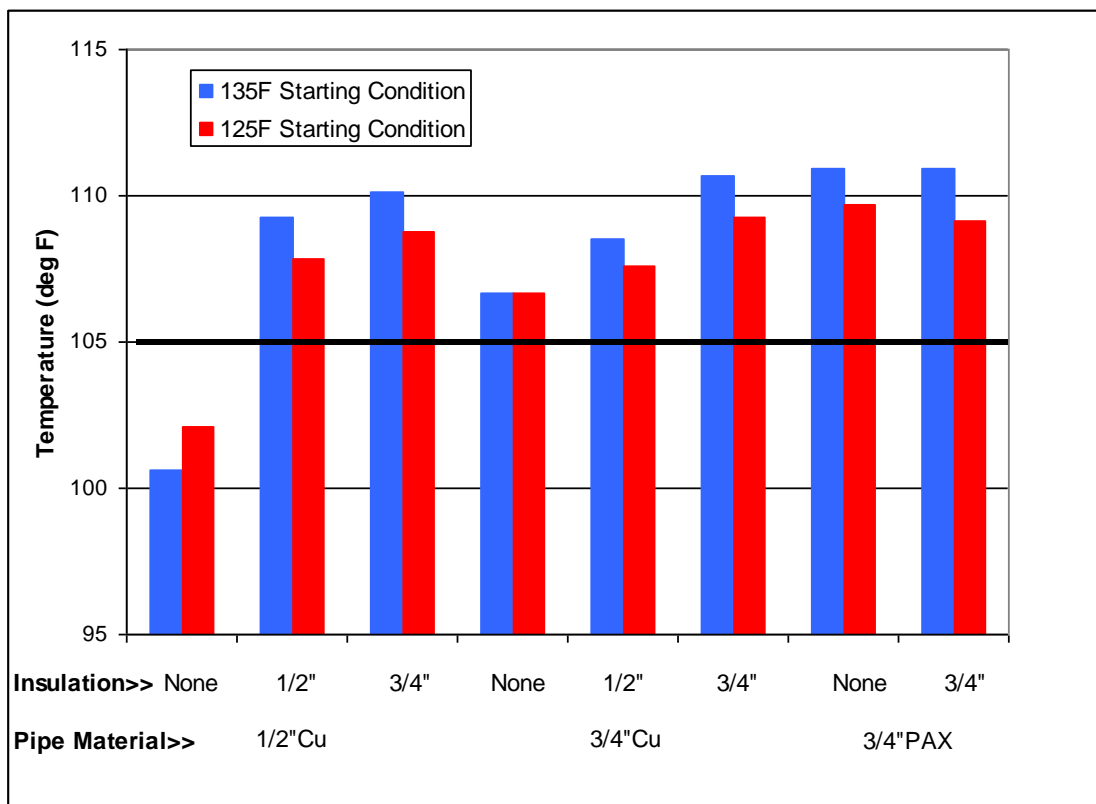


Figure 18. Initial Draw Temperatures After Cool-Down Period

³ Keep in mind that the Figure 18 reported temperatures represent projections at 14 to 64 minutes after the end of the hot water draw.

3.1.6. Complete CASE Initiatives for Single Family Water Heating.

Four Measure Information Templates for 2008 revision to the Building Energy Efficiency Standards (Title 24) were submitted to the Energy Commission for consideration. The proposals presented at a staff workshop on May 19, 2006 were:

- Tankless Gas Water Heaters
- Revise ACM Distribution System Multipliers (Table RG-2) and Eligibility Requirement
- PEX Parallel Piping Hot Water Distribution Systems
- Water and Wastewater Tariffs

These proposals were developed from the results described under other tasks in this report. The details of the recommendations are included in the next section of this report. The full proposals are included as appendices to this document and are available at the Energy Commission Building Energy Efficiency Standards web site

3.2. Support for the Super Efficient Gas Water Heating Appliance Initiative (SEGWHAI)

3.2.1. Gas Water Heater Energy Losses

All the energy in the simulation model ends up as useful hot water, heat stored or heat lost. Heat can be lost through the fittings and the jacket by conduction, convection and radiation and by hot combustion gases flowing up the flue. In addition, the uninsulated flue conducts heat from the water during standby hours which then moves up the flue by convection. The pilot energy consumption during standby is included in the energy input. Figure 19 shows the percentage of heat flow by each mechanism. The number of hours listed by each flow is how long it happens during the test.

Modeling showed that, without considering a condensing water heater design, the greatest potential efficiency gains can be made by reducing flue losses during the non-firing, non-recovery mode, i.e., during standby mode. Reducing heat losses up the flue during standby has the greatest potential for increasing water heater efficiency. Reducing jacket and fitting losses, while possibly less complicated to achieve, offer only a modest potential for increases in efficiency. The stack losses while in standby mode account for about 43% of heat losses (not including the energy added to the delivered hot water) and 17% if hot water energy is included.

The data in Figure 19 is from a simulation model run that had a lower water temperature at the end of the test than at the beginning. To correct for this, the test procedure subtracts the stored energy from the delivered hot water energy of 66% to provide the true net supplied efficiency of 61%.

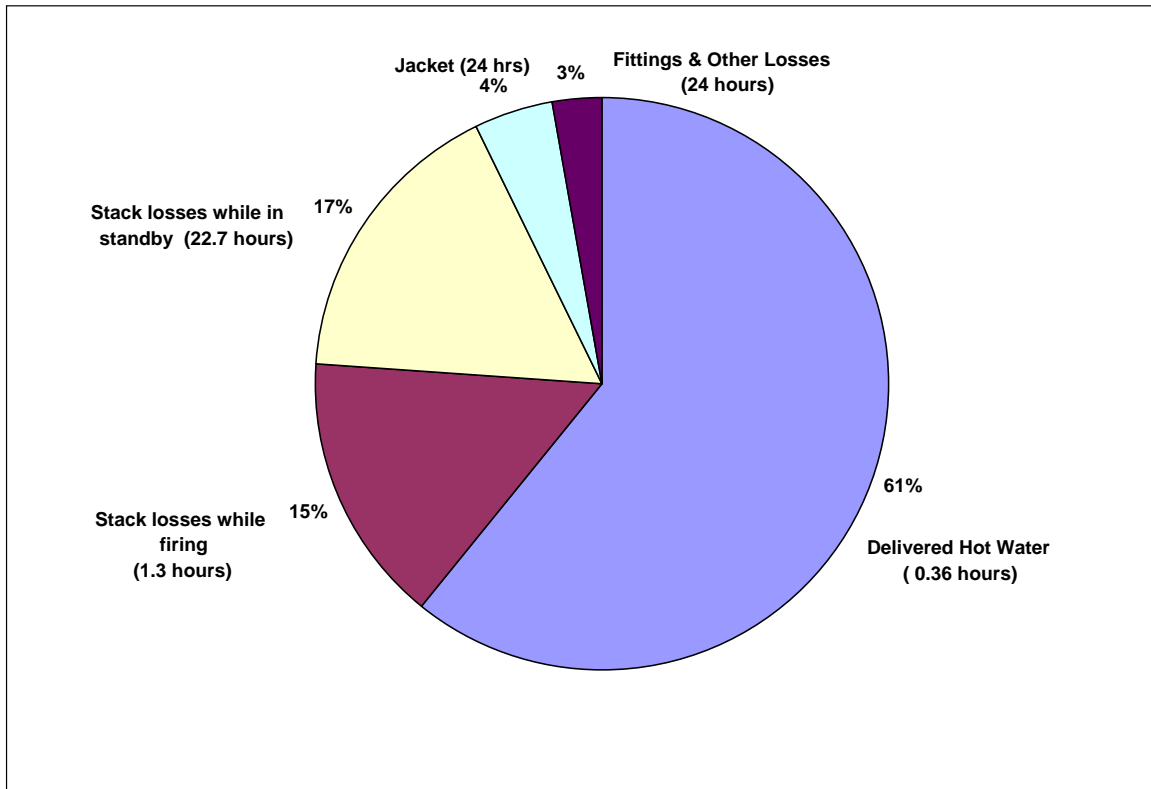


Figure 19. Energy Flows from Simulation of Gas-fired Storage Water Heater

Table 7 shows details of the energy flows in Figure 19. The losses are provided in BTU's as well as percentages of the total heat flows. The largest amount of input energy goes into heating the water. The next two largest heat flows are up the flue (stack loss) while in standby mode with only the pilot light on (17%) and while the burner is on and heating the water (15%). The standby mode represents the portion of the pilot light input that does not heat the water, i.e., is lost up the flue, as well as the heat transfer from the hot water in the tank through the uninsulated flue.

The heat losses through the 2 inches of insulation jacket are relatively small at 4%. Another 3% of total heat is lost through the fittings. The negative values for "storage" indicate that during this simulation some of the energy supplied to the delivered hot water was due to a drop in temperature (from the start of the test) of the water in the tank, the metal of the tank holding the water and the metal jacket protecting the tank insulation.

Table 7. Distribution of Energy Flows During Energy Factor Test

		Energy		
Energy Flow	Parameter	BTU's	Percent	Time (hours)
Input	Burner	52,552	85%	1.3
	Pilot	9,600	15%	24
Output	Delivered hot water	41,095	66%	0.36
	Stack loss on standby	10,404	17%	22.7
	Stack loss while firing	9,479	15%	1.3
	Jacket loss	2,771	4.5%	24
	Bottom skirt loss	998	1.6%	24
	Fitting losses	411	0.7%	24
	Inlet pipe (line) losses	307	0.5%	24
Temperature change	Water in tank	-2,971		
	Inner and bottom vessel metal	-64		
	Outer and top vessel metal	-55		
	Jacket metal	-35		

Figure 20 shows the percent heat losses (not including the delivered hot water), and not adjusting for the change in temperature of water in the tank of the metal tank and jacket.

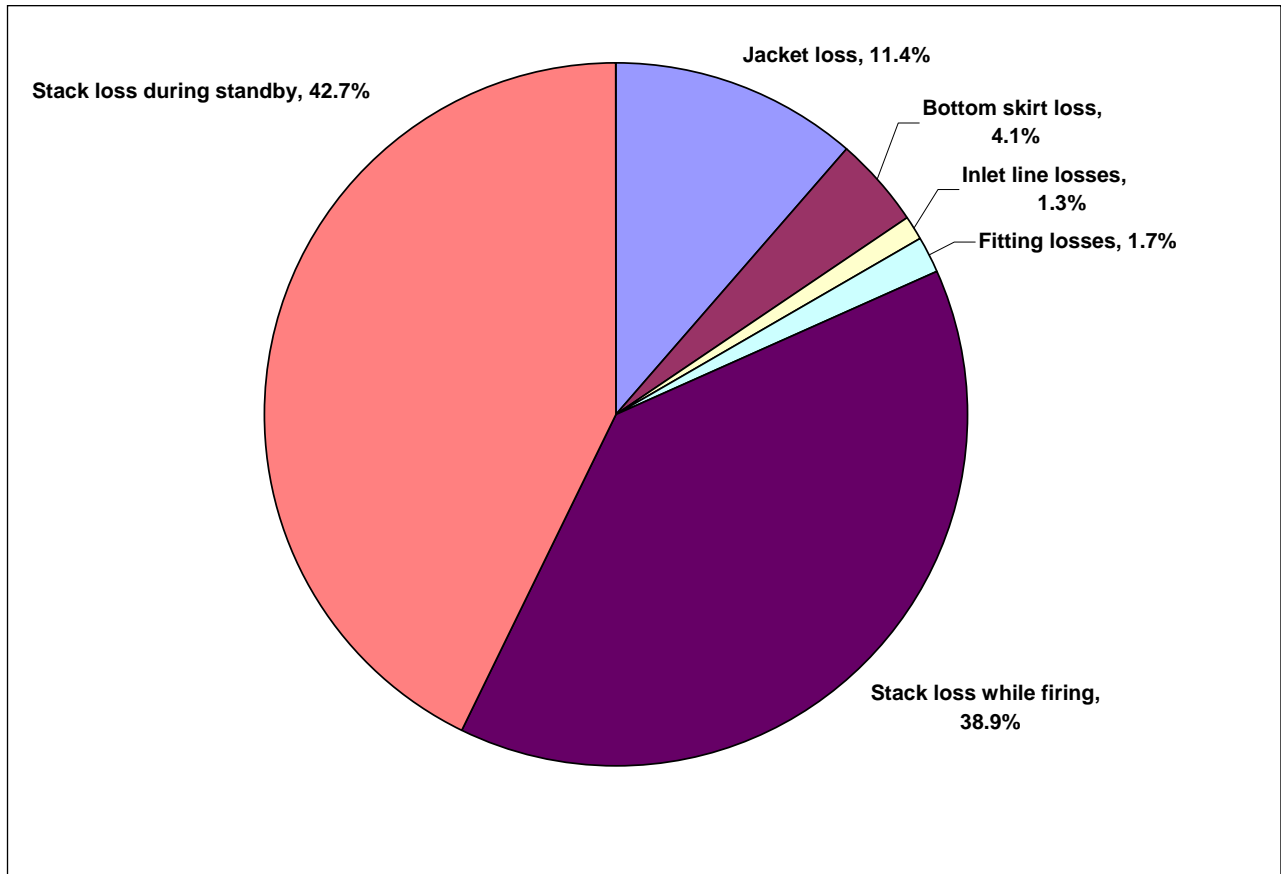


Figure 20. Percent Heat Losses from Tank

3.3. Existing Residential Hot Water Distribution Systems

This task developed tools and reports for future programs to accurately calculate the potential for energy savings from improvements to hot water distribution systems in existing single family homes.

3.3.1. Pilot mail survey of single-family house occupants

The following questions were added to a survey for the California Single-Family Residential Water Use Efficiency Study. These questions will help develop a better understanding of hot water distribution systems in existing single family homes.

- Please indicate whether you have renovated or replaced any of the following since 1995. (plumbing pipes, bathroom fixtures, kitchen fixtures)
- Do any of the showers in your home have multiple showerheads? (if yes, How many showerheads per shower?)
- What type is your water heater? (gas, electric, propane, solar, tankless / on-demand, other)
- Do you have a recirculating pump for your hot water heater?
- Does hot water take longer to reach some places in your house than others?

(No, hot water reaches all fixtures in about the same amount of time
or Yes, some places take longer than others for hot water to reach

if yes, which rooms, kitchen, master bathroom, other bathroom, other room)

- Thinking of the place in the house where it takes hot water the longest to reach, how long would you say you have to wait for hot water?

(Almost no time at all,

Not very long, we just have to let the water run for a few seconds,

Pretty long, we have to let the water run a while before it runs hot, or

Very long, we have to let the water run a long time before it runs hot.)

- Does the wait for hot water bother you?

(Yes, very much,

Yes, little bit, or

No, not really.)

3.3.2. Determine data needs of regulatory organizations

Unfortunately, the current plumbing codes do not differentiate between hot and cold potable water piping in the design and installation of a distribution system. Without this differentiation, current hot water distribution systems typically become over-sized while following the guidance provided by plumbing codes. Excessive pipe size has little or no negative water or energy conservation impact on cold water systems but it is a big factor in reducing the performance of hot water distribution systems.

Our review of the Uniform Plumbing Code (UPC) identified several areas that could be changed in order to reduce the water and energy wasted in hot water distribution systems as well as the waiting period for hot water to arrive at the fixture. Some of these changes would apply to all occupancies, while others would apply to single-family housing and multifamily housing with individual water heaters for each unit and could save significant resources. We have submitted a proposed change to the 2009 revision cycle.

Formal change request for IAPMO Technical Committee HWDS Definitions

The purpose of this proposed change is to define hot water distribution systems and to separate hot water distribution systems from potable water distribution systems to facilitate the evaluation of energy consumption and water waste as well as flow and pressure characteristics in their design. There is no intent to define hot water, only that portion of the piping system that distributes it.

Formal change request for IAPMO Technical Committee HWDS Chapter 6

The purpose of this proposed change is to more easily enable the separate calculation of Water Supply Fixture Units (WFSU) and Minimum Fixture Branch Sizes for hot and cold water distribution systems for all occupancies. The $\frac{3}{4}$ value previously permitted in the footnote as the basis for all fixtures served by both hot and cold water has now been formally incorporated into the table.

This change is very important because it more accurately reflects real water use in residential systems and can result in a potential reduction in pipe size which reduces energy and water waste.

Formal change request for IAPMO Technical Committee HWDS Appendix L

The purpose of this proposal is to revise the Water Supply Fixture Units (WSFU) for Bathroom Groups, Individual Dwelling Units to separate hot and cold water. The proposals distinguish between hot and cold water and stipulate the pipe sizes to be used unless engineering calculations indicate that a smaller diameter is acceptable or that a larger diameter is required. In addition, hot water has the same relative diversity factor for hot water consuming fixtures as cold water does for cold water consuming fixtures.

Formal change request for IAPMO Technical Committee HWDS Buried Conduit

All buried potable water piping shall be installed in a waterproof channel or conduit that allows for removal, repair and replacement. Elbows shall be gradual, wide radius bends. The internal cross-section or diameter of the channel or conduit shall be large enough to allow for removal and reinstallation as well as insulation of the potable hot water piping.

When piping is accessible, it is relatively straightforward and inexpensive to repair or replace. It is well known that identifying and repairing leaks in under slab piping is expensive. It will get even more expensive if the trend toward post-tension construction for concrete slabs continues. Installing potable water piping in a conduit is reasonable given that historically houses generally last longer than their plumbing systems.

Electrical wiring that is buried within or under a slab floor is installed in a waterproof channel or conduit from which it can be removed, repaired and replaced if it becomes necessary to do so. The rationale is that the same should be done for potable water piping.

3.3.3. Assess potential sensing and monitoring technologies

This subtask identified and evaluated sensing and monitoring technologies and techniques to support plumbing code changes related to HWDS. These sensing and monitoring technologies could be candidates for use in future field monitoring studies.

Studies have shown that hot water use patterns have a major (if not dominant) impact on how a specific hot water distribution system (HWDS) will perform. Yet at the same time there is little documented information on how people actually use these systems. This situation has forced a “best guess” approach to defining the use patterns—leading to a lack of confidence in requested code changes and recommended design standards. The data obtained from a large scale sampling could be utilized to substantiate the potential energy code (Title 24) and plumbing code (Uniform Plumbing Code) changes. The data could also be used in HWDS optimization simulation studies that could lead to best practices recommendations for system configuration.

A literature review of previous HWDS studies was undertaken to see what could be learned from previous experience.

Past studies have by-and-large had a relatively narrow focus that considered specific issues/topics such as demographics (number of occupants, age, renter/owner), seasonal

variation or type of water heater. Temperature-based event studies are more accurate (97.1%) but were not broad based with a very limited sampling of homes. The flow trace signature analysis studies are less accurate (90.6%) but have been larger in scope with significantly more houses evaluated. The existing studies are based on very limited field data which raises questions of its validity.

A list of available sensing and monitoring product was developed that could identify when the water has been turned on and the temperature of the water (to identify the arrival of hot water). The equipment would be placed in private homes, so it is very important that the equipment be easy to install/remove as well as not damage the home or degrade the integrity of the water system.

3.3.4. Bench test key elements of sensing and monitoring technologies

Piping was purchased from a local home improvement store typical of piping used in domestic household water systems. The pipe materials were copper, CPVC and PEX in sizes ½ inch and ¾ inch. Six test pieces were made from the sample pipes with all having thermocouples affixed at the same location in respect to each other. An ungrounded, sheathed, 1/16 inch, stainless steel thermocouple was inserted midway into the water stream while an ungrounded, stick-on 30 gage thermocouple was affixed to the outside of the pipe wall 2 inches upstream of the immersed thermocouple. Heated 135°F water was pumped through the horizontal test sections at ½, 1 and 2 gallons per minute. The tests took place in an environmental chamber with the ambient air temperature controlled at 70°F. During each test measurements were recorded and plotted in 2 second intervals for a period of 180 seconds. The plots include a short period of the steady-state, pre-test conditions for informational purposes. Estimated time lag and temperature differences between immersed thermocouples and surface mounted thermocouples are shown in Table 9.

Table 8. Differences between immersed and surface mounted thermocouples

Pipe Material	Pipe Size (nominal inch)	Flow rate (GPM)	lag (s) ^a	temperature difference (°F) ^b
Copper	½	0.5	5	5
		1.0	2	5
		2.0	1	4
	¾	0.5	7	4
		1.0	4	5
		2.0	3	5
CPVC	½	0.5	20	18
		1.0	15	16
		2.0	12	18
	¾	0.5	45	>20?

		1.0	15	22
		2.0	15	21
PEX	$\frac{1}{2}$	0.5	12	11
		1.0	8	10
		2.0	10	10
	$\frac{3}{4}$	0.5	15	20
		1.0	10	18
		2.0	8	12

a - time lag estimated at 80°F

b - temperature difference estimated after 140 seconds.

4.0 Conclusions and Recommendations

The conclusions presented here are drawn from the individual reports which are attached as appendices to this final report. The conclusions are listed in the same order as the objectives presented earlier. Specific recommendations for future research, where appropriate are presented along with the conclusions.

4.1. Development of Hot Water Distribution System Recommendations for the 2008 Title-24 Residential Building Energy Efficiency Standards

4.1.1. Multi-Family Water Heating Construction Practices,

Pricing and Availability Survey Report

Central DHW systems are more common in southern California than in northern California. They are also more common in high-rise projects and in dense urban areas rather than in low-rise projects or in low-density areas. Timer controls (current Title 24 minimally compliant control) and the temperature controls were priced between \$23 and \$200 and that the temperature modulation controls were priced between \$750 and \$2000. Timer and the temperature controls are the most commonly used controls for recirculation loops in central DHW systems and that there is little market awareness of demand type or temperature modulation type controls. In other research conducted as part of the larger project this survey falls under, we find that timer and temperature controls are not very effective compared to demand and temperature modulation controls at realizing energy savings. Because respondents to the survey reported reasonable pricing and quick installation times for the demand and temperature modulation controls, we believe that these controls are ready to be incorporated into the code to increase market penetration and realize savings.

Many engineers and energy consultants indicated that they specify insulation on DHW pipes as mandated by code. However, they could not say with certainty that the insulation had actually been installed on site as specified. We conclude that the enforcement of code requirements for insulation in recirculation pipes is important to reduce hot water distribution losses in multifamily buildings. We recommend that this code requirement should actively be enforced by verifying that the insulation is in fact installed on site as indicated on the drawings.

Controls Performance Field Report

DHW systems in multifamily buildings are very complex and it proved difficult to locate sites that were suitable candidates for this study. The monitored sites included a few challenges, for instance the Oakland site has a short additional pipe that allows cold water (or hot return water) to flow into the hot water supply pipe via a thermostatic mixing valve. We did not have sufficient equipment to instrument this “shortcut” loop, but it appeared that the magnitude of the flow (if any) was not large enough to affect the calculations. Also, the boiler at the Emeryville site was a modulating boiler, so we could not use the gas burner on-time as a direct

proxy for energy use. This removed an important checking mechanism that was available at the other two sites.

Due to the question-marks over some of the data, the analysis for this study involved a great deal of cross-checking. We applied two analysis approaches to evaluate energy and water consumption by the four recirculation control schemes. It should also be remembered that the results include only four weeks' data at three sites, so should not be taken to accurately reflect statewide conditions.

In addition, the St Helena system was missing recirculation loop insulation, so the savings achieved by advanced controls at that site are likely to be greater than those that would be achieved in a new Title 24 compliant system.

Energy Savings from Control Systems

It is clear from the data that the control systems made a significant difference to the gas consumption at all of the sites. At the Oakland site none of the control systems appeared to make a significant difference, perhaps because the Oakland system was delivering comparatively low temperature DHW before the on-site survey began.

The timeclock controls did not save significant amount of energy at either of the two sites at which they were installed. Timeclock control was not installed at Emeryville because the logged data showed that there was hot water demand throughout the night, so a timeclock would not have been a suitable solution.

Table 9. Energy Savings From Control Systems, Compared to Continuous Pumping
(based on gas consumption)

	St Helena	Emeryville ⁴	Oakland
Timeclock	1.5%		-1.1%
Demand	44.1%	35.0%	-5.3%
Temperature modulation	35.0%	47.0%	5.5%

Across the three buildings, demand control systems and temperature modulation systems saved an average of 27% of the gas consumption, compared with continuous pumping with the tank stat set to maintain the storage tank water at between 115°F and 135°F.

Note that in this study the baseline condition was continuous pumping with the storage tank aquastat left at the same level it was found at by the experimenters. At St Helena and Emeryville, and to some extent at Oakland, the aquastat set point was high, resulting in high supply and return temperatures and therefore in high energy use. The savings shown above for the demand and temperature modulation systems are therefore relative to the as-found condition of the DHW systems, rather than relative to what could ideally be achieved with

⁴ Note that the Emeryville site has a modulating boiler, and the measured gas savings are based on gas valve on-time, *not* the actual amount of gas consumed, therefore the actual savings may be different from the values shown in the table.

continuous pumping or timeclock control. This comparison is fair to the extent that the high as-found aquastat setpoints may be due to recirculation pump failures that might be less likely with demand and temperature modulation controls.

Water Savings from Control Systems

The results on water consumption are inconclusive. When the flow was analyzed assuming a constant crossover flow, all the control systems saved water compared to continuous pumping, but when the flow was analyzed assuming zero crossover flow, many of the control systems used more water (see Figure XXX)

There are three logical reasons why a slight increase in water consumption might be expected from the two advanced control systems. First, if the system allows water in the loop to cool (timeclock control, demand control), tenants might have to “run out” more cold water before getting hot water. Second, if the system reduced the temperature of hot water (temperature modulation), tenants would need more hot water to make up their desired temperature (although a proportional reduction in cold water use could also be expected). Third, leaks in the system might be increased or decreased by the recirculation pump being switched on.

However, given the natural variability in the results caused by the short monitoring period and small number of buildings, we cannot draw any firm conclusions about the effect of controls on water consumption.

The observed changes in water usage (assuming constant crossover) are the exact reverse of what would be expected based on the rationale described above (the temperature modulation and demand controls supplied water at a lower temperature than the continuous pumping control). It is possible that tenants receiving very hot water (above 130°F) or water at an unpredictable temperature may take longer to temper that water down to around 100-105°F for a shower or other end-use, and may therefore use more hot water while adjusting the temperature. Note that the water consumption during the timeclock control period at St Helena was extremely low. We are not able to explain this low figure.

Table 10. Water Savings from Control Systems, as a Percentage of Continuous Pumping,
Assuming Constant Crossover

	Crossover assumption	St Helena	Emeryville	Oakland
Timeclock	Constant	47%		-5%
	Zero	47%		-5%
Demand	Constant	16%	28%	12%
	Zero	19%	-22%	3%
Temperature modulation	Constant	11%	21%	N/A
	Zero	37%	-6%	N/A

Condition of Systems in Real Buildings

In the three buildings studied, we found failed or overridden timeclocks, failed recirculation pumps, and a wide variety of supply and return temperatures including excessively high temperatures that waste energy and may cause scalding. The staff we spoke to in these buildings were, in general, not aware of these problems.

We cannot judge whether these problems have existed since the installation of the systems, or whether they have developed over time, but these limited results suggest that a great deal of energy may be wasted in multifamily buildings throughout the state because of failed DHW system components and incorrect system setpoints. These problems may be remedied by initial commissioning, retrocommissioning, or by continuous automatic monitoring with fault reporting and diagnosis (as per the two advanced control systems tested).

Use of Ultrasonic Transit Time Flow meters

The data for hot water supply and hot water return flow rate was significantly in error, in all three buildings and under all control schemes. We attribute these errors to two problems. First, the acoustic coupling gel between the transducer and the pipe was observed to leak out during the monitoring period, on the hotter pipes. The meter manufacturer advised us that there are different gels available that are more tolerant of hot temperature. If we were to use the ultrasonic meters again for long-term monitoring we would need to keep checking the gel at regular intervals.

Second, the meters measure only the velocity of flow, i.e., they do not measure volumetric flow rate directly. Therefore if the internal pipe diameter is less than expected (for instance due to mineral deposits inside the pipe) the meter would give too high a reading. From conversations with experts in the field we believe that mineral deposits on copper pipes may be common in California.

In future research we will therefore use flow meters that directly measure volumetric flow rate.

Conclusions in Regard to Title 24

Failure of Recirculation Pumps

We found that the recirculation pump had failed at one of the test sites, and results developed jointly by EDC Controls and HMG suggest that recirculation pump failure may be very common. It may be possible within Title 24 to take steps to improve recirculation pump reliability.

Hot Water Draw Magnitude

The magnitude of draw measured on site was slightly higher than the amount predicted by Title 24 2005 Equation RG-9. However, given the small number of sites surveyed and the expected high degree of variation between one system and another in terms of leaks, crossover flow, the number of faucets and the flow velocity of faucets, we are not able to conclude that the draw magnitudes predicted by Title 24 are not representative of typical conditions in buildings.

Hot Water Draw Schedules

The shape of the hourly hot water draw schedules measured on site were distinctly different from the residential profile in Title 24 2005. In all three sites the schedule is flatter--the morning peak is less pronounced and the evening peak is broader. Overnight the flow drops to near zero, the same as the Title 24 schedule.

Because these schedules represent data from 149 apartments over a period of 4 weeks, we are confident that the difference in draw schedule is real and that Title 24 should include a draw schedule specific to multifamily buildings.

Total DHW Energy Savings from Control Systems

Both demand control and temperature modulation control demonstrate energy savings across the three sites. High variation in energy savings was observed, due to system configuration differences among the three surveyed sites and the date accuracy issues related to measurement instruments. Each control system demonstrated unique performance characteristics.

Further modeling and field studies is required to quantify the savings potential for both control schemes. Future Title 24 may include provisions to provide credit for these two control systems.

Recirculation Loop Energy Savings from Control Systems

Title 24 includes an allowance for advanced control systems, which is applied to the recirculation loop energy consumption. Therefore, the amount of energy saved in the recirculation loop by advanced controls is a relevant question for future revisions of Title 24. It should be noted that the advanced controls achieve their energy savings mainly in the recirculation loop, although some savings are also achieved by reduced storage tank losses in the case of temperature modulation systems.

According to the results shown in Figure 24 through Figure 26, the recirculation loop and storage tank together account for between 11% (Oakland) and 63% (St Helena) of the total gas consumption (26% at Emeryville). Therefore, the savings expressed as a percentage of the loop energy consumption would be proportionally higher than the savings expressed as a percentage of total energy consumption.

Further Research

Earlier research studies, utility programs and codes and standards have addressed the theoretical performance of systems in buildings. But this study, as well as other recent studies in different fields, including HVAC and lighting, have revealed wide variations in performance between systems once they have been installed and operated for a period of time.

These studies have revealed opportunities for energy savings that were not predicted by theoretical models, and have shown that unexpected equipment failures or maintenance issues mean that theoretical savings are often not achieved without additional, supporting measures or technologies.

This study has brought several new issues to light (crossover flow, pump failure) and has generated data on the savings from various control systems. However, because this study included only three multifamily buildings, further field research is required to explore the reasons for pump failures and crossover flow, and to provide more data on the savings achieved by different control systems under various circumstances. This field research should shed light on what aspects of system design, operation and maintenance offer the greatest opportunities for cost-effective energy savings.

Recent cost reductions in the technologies required for remote telemetry have led to several manufacturers offering control systems that provide performance monitoring, fault detection and diagnosis in real time, and provide feedback to the customer on energy performance and on system faults. These systems have been in place for up to ten years, and have become much more widespread since 2004, so they are sufficiently mature to be evaluated for their effectiveness and for potential inclusion in future revisions of Title 24.

These systems provide a basis for moving toward “continuous commissioning” of DHW systems. Continuous commissioning has proven effective in increasing the efficiency of HVAC systems, and research by HMG and by others indicates that lighting control systems would also benefit. The lessons learned in these other technology areas could be leveraged for DHW.

At present, there is no statistically valid baseline for the energy performance of central DHW systems, so one focus of future research should be on creating a baseline that can be used for more accurate calculations of potential savings from new technologies and new measures.

We suggest that the following issues should be addressed in future research:

- The existing condition of central DHW systems in multifamily (MF) buildings with recirculation pumps.
- Types of failure commonly occur in these systems.
- Whether recirculation pump failures are caused by air in the recirculation line, and whether this failure mode can be addressed by installing air release valves.
- The effect on water and gas usage from cross-flow between hot and cold water and the level of cross-flow reduction by installing a check valve on the cold water supply pipe.
- The effect that demand controls and temperature modulation controls have on water and gas usage over a large number of sites that include a variety of geographic locations, building types and occupancy types.
- The development and testing of a protocol for commissioning (or acceptance testing) of MF DHW systems that will inform changes to Title 24 2011, along with recommendations about continuous commissioning procedures.
- The effect of commissioning, performance monitoring, fault detection and diagnostics (PM, FD&D) on the functional state of systems, and their water and gas usage.

- Hourly schedules for water and gas usage in MF buildings throughout the state, and how these are affected by climate zone, season, temperature, precipitation⁵, building type, demographics, and system type.
- The relationship between water flow and gas usage, so that water draw schedules can reliably be derived from gas usage schedules, and vice-versa.
- Whether vent dampers on gas water heaters provide verifiable energy savings and/or cause unacceptable maintenance problems.

Proposed Multi-Family Water Heating Changes Codes and Standards Enhancement (CASE) Report

Recommendations

Proposed HARL Equations

The HARL equations should be adjusted in the light of further data analysis from this project and from others involved in the current LBNL hot water research, in time for the 2008 Title 24 revisions.

Proposed Adjustment Factors and Controls Credits

The adjustment factors and controls credits should be adjusted in the light of further data analysis from this project and from others involved in the current LBNL hot water research, in time for the 2008 Title 24 revisions.

Proposed Daily Draw Schedules

A multifamily-specific draw schedule should be developed from the monitored data from this project, and from other research sources, in time for the 2008 Title 24 revisions.

Proposed Water Heating Budget

Using monitored data from this project we will develop a proposal that quantifies the effect of the number of bedrooms (in addition to the number of dwellings) on heating budget.

Proposed Verification

For the proposed measures, a combination of construction inspection and Performance Testing would be required to ensure that the system is operating adequately.

Verification Requirements

Check valves:

⁵ Anecdotal data and personal experience from EDC Technologies indicates that rain leads to a short-term increase in gas usage, possibly because people take more, longer or hotter showers, or because underground pipes or pipes within the building are cooled by rain.

- Construction Inspection: Insure check valves are present as necessary, according to the plans, are of the specified type and size, and are installed in the correct flow direction.

Water measurements:

- Construction Inspection: When multiple hot water recirculation loops are driven by a single pump, it is recommended that the system should be balanced per the procedures defined by the Testing Adjusting and Balancing Bureau (TABB) National Standards.

Air release valve:

- Construction Inspection: Insure air release valves are present as necessary, according to the plans, are of the specified type and size, and are installed in the correct orientation.
- Testing: Test the equipment and verify the correct operation.

Recirculation pump:

- Construction Inspection: Insure recirculation pumps are present as necessary, according to the plans, are of the specified type and size, and are installed in the correct flow direction.

Control Systems:

- Testing: Test that all the sensors are communicating with the controller correctly. For temperature modulation controls this includes the pump operation signal (pump on and off) and the temperature sensor(s). For demand controls this includes the flow sensor and temperature sensor(s).
- Testing: Test that the system is functioning within the bounds established by the design documents.

Hot water pipe insulation:

- Construction Inspection: Insure pipe insulation is present as necessary, according to the plans, and is of the specified type and size. Insure insulation is continuous and no gaps are present between sections.

Material for Compliance Manuals

Add the following choices to Table R3-9 of the Res ACM.

Table 11. Multiple Dwelling Unit Recirculating System Control Choices

Distribution System Measure	Code	Description
Temperature Control	RTmp	Recirculation system, with an aquastat control to switch recirc pump on and off
Timer/Temperature Control	RTmTmp	Recirculation system, with a timeclock and temperature control
Temperature Modulation Control	RTmpMod	Recirculation system, with the water heater temperature setpoint controlled to vary the intensity depending on the load

Demand Control	RDmd	Recirculation system, with demand control on the recirc pump
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Revise the equations for the calculation of Hourly Adjusted Recovery Load (HARL) in Appendix RG (Water Heating Calculation Method) of the Res ACM to reflect a more accurate calculation of the Hourly Recirculation Distribution Loss (HRDL), which is a component of the HARL.

Based on our hot water draw schedule research, we will propose a new table with hourly fractions specifically suited to multifamily buildings. This table would be in addition to Table RG-1 (Hourly Water Heating Schedule) in Appendix RG of the Res ACM that can be used for single family homes.

Future Work

Additional Research

There is a significant amount of additional research that is needed on this topic. For example, although the data set leading to the recommendations in this report are extensive in terms of evaluating the impact of several control strategies in a number of settings, clearly the sample size is not sufficient to be definitive. We recommend a replication of this research on a much larger set of buildings, with a larger variety of hot water system types. At a minimum, twenty more buildings should be monitored including:

- High-rise MF (both for-sale and for-rent)
- Single room occupancy buildings (this is an expanding segment)
- Senior MF housing
- Buildings with multiple, staged boilers
- Buildings with boilers with OEM modulating controls
- Buildings with water heaters
- Boilers or water heaters located outside the building
- Systems with underground piping

Future work should also determine the extent of seasonal variations in:

- Hot water demand
- Heat loss and system performance based on outside air temp
- Cold water temp and its impact
- Gas consumption based on the above factors and gas delivery temp

A more extensive economic analysis also needs to include seasonal variations in gas prices and pricing structures. This analysis, for example, should include the forecast cost of propane in the areas of the state not served by natural gas.

Acceptance Testing Protocols

Protocols need to be established, and added to the Residential Compliance Manual, for Acceptance Testing for central water heating features that are mandatory or prescribed. Currently, absence of an Acceptance Testing protocol results in violations of the code going unnoticed.

Commissioning and Monitoring

For the 2011 standards it may be desirable to move toward a goal of requiring permanent monitoring and “continuous commissioning” of controls, given the expected continuing reductions in the cost of collecting, transmitting and storing monitored data on installed systems. This data will be a great asset for future research and Code change proposals.

Before monitoring of installed systems can be required by Code, the benefits of monitoring must be established in field trials, perhaps in conjunction with existing logged data from controls system vendors.

Recirculation Loop Insulation

Data collected from Architects, Plumbing Engineers, Energy Consultants, and Developers shows that recirculation loop pipes are usually insulated either to code or better than code, depending on the location of the pipes.

In some cases however, the pipes are not insulated, which is a violation of the code. However, prior to the 2005 revisions to the Building Energy Efficiency Standards, this code requirement was arguably ambiguous. None of the Building Departments surveyed have kept a copy of the plumbing drawings for MF buildings after a project has passed its final inspection. Some Building Departments check the plumbing drawings set at the time of processing the permit, but even this is not always the case. As a result, if there is a code violation, such as lack of the mandatory minimum insulation in the recirculation pipes, it is practically impossible to check it once the project has been built and the pipes are buried. It was evident during the surveys that knowledge of this fact resulted in a degree of complacency among the developers and plumbers regarding pipe insulation.

Developing an Acceptance Testing protocol for recirculation loop insulation will result in savings. The cost to insulate pipes was quoted as 25 cents to 47 cents per linear foot by one source.

Vent dampers

Vent dampers are currently not required by code, and may present a significant opportunity for energy savings at low cost.

Other Features Recommended for Future Acceptance Testing

- Verify Hot Water Supply and Hot Water Return temperatures are in acceptable range

- If multiple recirculation loops exist on a single system, then verify that each pump size is properly balanced for each loop.
- Verify flow sensor operates properly in a Demand Control system

4.1.2. Pipe Heat Loss Testing

The addition of pipe insulation dramatically reduces pipe heat loss, resulting in AF/PV ratios of the insulated buried pipe being similar to similar bare and insulated pipe in air.

In summary, placing uninsulated hot water distribution piping in a buried environment is highly energy inefficient. Adding insulation to buried hot water distribution piping substantially reduces energy waste, at least in damp, but not saturated environments. Performance of buried pipe insulation in a saturated (liquid water present) environment has not been investigated, but is expected to be poorer than in damp environments. Moreover, longevity of buried pipe insulation has not been investigated. Some deterioration of insulation performance would be expected over time due to eventual moisture migration into the insulation, biological attack (mold, fungus), boring insects (e.g. ants, termites, beetles, worms, larvae), rodents, root intrusion and other effects.

4.1.3. Characterize Single Family Water Heating Construction Practice

Single Family Water Heating Construction Practice Survey

The following conclusions were generated based on the field experiences during the sixty home survey:

- PEX has achieved significant market share in the last few years with a strong trend from copper piping to PEX piping. This was especially true in Northern California. All areas of the state where PEX is allowed show fairly rapid transition to this material. The input from plumbers who have switched to PEX is that the system is cheaper to install, can utilize less skilled labor, and is less prone to leaks.
- Plumbers cite two reasons in not changing to PEX. First, the City of Los Angeles does not allow PEX in their jurisdiction and that prevents some other southern California jurisdictions from allowing PEX. Secondly, many plumbing contractors are reluctant to install newer products for fear of future liability and specifically cite the polybutylene failures from the 1980's as the reason not to switch to PEX. These two reasons are slowing the transition to PEX in Southern California.
- Systems of all types were generally not efficiently installed. The following summarizes findings on each of the system types:

Trunk & Branch and Hybrid Systems

Eliminating excessive pipe length is most important improvement that could be implemented in both trunk & branch and the hybrid system types. Installers seem to put little value on reducing pipe length despite the benefits of reduced hot water waiting time (less callbacks). Designing a system with an emphasis on reducing piping length would have lower material costs, lower installation labor costs, and would provide better performance. For some reason installers tend to run trunks parallel to framing rather than straight to where the hot water is needed. This

trend adds about 40% to the length of the trunk. This isn't a trend with forced air duct systems why is it typical with plastic piping?

Parallel Piping - Manifold Systems

Eliminating excessive pipe length is also the most important improvement that can be made to parallel piping systems, but the improvement is much easier. The majority of the excess pipe length is found in the main between the water heater and the manifold. The water heater and the manifold are typically located adjacent to each other but the piping that connects the two is often routed by other than a direct route. In one case there was 24 feet of one-inch pipe between the water heater and the manifold. On average, reducing the observed length to a maximum of 10 feet would reduce the entrained volume of the manifold systems by 26%. (Reducing this length by running the main out the side of the manifold cabinet and directly to the water heater could reduce this length to about 3 feet.) Another pipe length reduction opportunity exists for two-story houses. Some, but not all, plumbers tend to run the piping to the attic and then back down to the first floor – even if the draw point is only 10 feet away. The preferred approach would be to remain between floors.

One issue that needs further study is the energy impact of tightly bundling hot and cold piping together. This was seen in some cases. The bundling was apparently done to consolidate the tubing in one location and make the piping installation look better.

Hot Water Recirculation Systems

Eliminating excessive pipe length is also a major issue for recirculation systems. In fact the problem is more significant than for other system types since excess pipe length is usually large diameter piping (3/4" or 1"). For the twelve recirculation sites surveyed, the average recirc loop entrained volume was found to be 4.42 gallons. Return line sizing was found to average 0.99 gallons and runouts (from the loop to the fixtures) were 0.17 gallons on average. For continuous or timer controlled loops, the large loop size has significant energy impacts. For the preferred demand recirculation approach, the data reinforces the need to fully understand how these systems are installed and controlled.

- Although parallel piping systems utilize roughly twice the length of piping relative to conventional plumbing practice, the entrained volume (per unit of floor area) was the least of the four system types. Additional significant volume reductions can be achieved with parallel piping systems by shortening the length of the main line between the water heater and the manifold. A 26% average volume reduction was calculated for the manifold systems if the length of the main could be reduced to 10 feet.
- Title 24 eligibility criteria for all system types should be carefully reviewed to insure that the systems being installed are properly credited or penalized.
- Six house plans will be developed for use in the Title 24 analysis process. Our proposal is to have one-story plans with floor areas of 1367, 2010, and 3,080 ft² and two-story plans with floor areas of 1,408, 2,811, and 4,402 ft². The "volume/1000 ft²" metric should be used as guidance in determining pipe lengths and pipe diameters in laying out the plumbing system.

HWDS Materials and Equipment Suppliers Survey

Three groups were approached for information on residential hot water distribution systems. Of the eight associations queried, none have provided information. Of the twelve manufacturers/distributors, one has provided information. Of the eight builders, three have responded with information. Given that the respondents are not representative of their entire industries, the information received cannot be aggregated and conclusions drawn on current building practices or future building trends. No effort has been made to merge the builder information. Such effort should not be made since these responses cannot be assumed to represent building practices in California.

Current Trends in California Single Family New Construction

Taken as a uniformly distributed group these six houses somewhat exceed the area and number of bathrooms reflected in the 2004 housing characteristics data. However, data from the past 30 years indicates that these characteristics are steadily growing. Since these houses are intended to reflect conditions for the 2008 revision of Title 24, this increase is considered appropriate.

Household Size - The number of person per household which impacts both overall hot water consumption and the pattern of that consumption will vary from the suggested occupancy shown above. This will occur both between different houses of the same type and over time in any given house as families change in size and age. For example, using a minimum of one person per household and a maximum of two-persons-per-bedroom as a rule of thumb, House 1 could have as few as one and as many four occupants. House 2 could have as few as one and as many as six. House 3 could have as few as one and as many as six. House 4 could have as few as one and as many as eight. House 5 could have as few as one and as many as eight. House 6 could have as few as one and as many as ten.

In addition the Census data indicated that some California residences were “crowded” (6.1%) and “severely crowded” (9.1%). If it is assumed that living, dining, family, den, study, and bedrooms are counted as rooms in the overcrowded house data, then House 1 with four rooms and would be considered crowded with four occupants and severely crowded with six or more occupants. House 2 with five rooms and would be considered crowded with five occupants and severely crowded with eight or more occupants. House 3 with six rooms and would be considered crowded with six occupants and severely crowded with nine or more occupants. House 4 with seven rooms and would be considered crowded with seven occupants and severely crowded with eleven or more occupants. House 5 with eight rooms and would be considered crowded with eight occupants and severely crowded with twelve or more occupants. House 6 with nine rooms and would be considered crowded with nine occupants and severely crowded with fourteen or more occupants.

Given this potential broad range of occupancies it may be advisable to use both a “typical” and “high occupancy” water consumption rate and use pattern when evaluating the various options being considered in the revised Title 24.

The Census data also suggests that overcrowding is related to ethnic and economic status. It also observes that overcrowding is more pronounced in multifamily housing. These factors

suggest that overcrowding may not need to be considered in larger, more costly homes. It is recommended that only Houses 1-3 be evaluated for overcrowding.

Single Family Prototype Floor Plans and Piping Layouts

Based on current new home construction characteristics, three of the floor plans were selected to be single story homes and the remaining three were selected as two-story. The selected floor area ranges were intended to bracket reasonable floor area ranges for one and two-story homes, respectively, and also provide a midpoint house size. Table 12 summarizes the six house plans.

Table 12, Description of Prototype Floor Plans

Plan Floor Area (ft²)	Number of Stories	Source of House Plan
1,367	One	2006 Sixty Home Survey
2,010	One	2005 Title 24 Evaluation
3,080	One	2005 Title 24 Evaluation
1,430	Two	2006 Sixty Home Survey
2,811	Two	2005 Title 24 Evaluation
4,402	Two	2006 Sixty Home Survey

Characterization of “typical” layouts was based on volumetric data reported in the sixty home field survey (Task 2.3 project report entitled *Field Survey Report: Documentation of Hot Water Distribution Systems in Sixty New California Production Homes*). The field survey report found that the average entrained volume⁶ for conventional trunk and branch plumbing systems was 0.49 gallons per 1,000 ft² of conditioned floor area. Using this as a goal, plumbing layouts were generated. In some cases garage water heater locations were shifted to allow the resulting average volume to come in within 5% of the goal.

4.1.4. Collect Supporting Information for the 2008 Standards Development Process

Hot Water Draw Patterns: Findings from Field Studies

The hourly water heating schedules used in the Title 24 water heating calculations should be replaced with the newer schedules using data from the studies in this report.

Although the data in this report indicate that the correlation of average daily hot water use with floor area is low, there is as yet no basis for changing the Title 24 calculation method.

The average number of draws per day is higher than expected. This will have impacts on the start-up losses for tankless water heaters and losses in hot water distribution system.

Investigating and collecting data from other studies for possible inclusion in the database would expand the number and type of houses in the database.

⁶ between the water heater and hot water end use points

Further analysis of this database could help to revise the water heating energy calculations for the 2011 version of Title 24 so that it is more representative of hot water use in single family homes in California.

Water and Wastewater Tariff Report

The unweighted average value for the 11th hundred cubic feet (HCF) of water, including the zeroes for flat rate tariffs, was \$1.40. The average of the non-zero values was \$1.52/HCF.

The average marginal cost per HCF of waste water, including zeroes for all 41 of the flat rate utilities, was \$0.74/HCF. The average of the non-zero values was \$3.23/HCF.

Ground Heat Transfer Algorithm Report

Following are summary recommendations for an appropriate model for under-slab hot water distribution piping in support of an improved energy efficiency standard.

- The model should capture all significant properties and characteristics of materials and components of under-slab piping configurations.
- Transient effects and interactions should be treated explicitly in the model.
- A numerical (e.g., finite element, finite-difference, or response factor) model is preferable to a purely analytical (e.g., cylindrical source or linear source) model.
- The model should be capable of longer-term (e.g., annual) simulations.
- To conserve computer run time, the model should employ a technique to aggregate past time steps (water draw events) that do not markedly influence each succeeding time step (water draw event) in the simulation.

Instantaneous Gas Water Heater LDEF Report (Field and Laboratory Testing of Tankless Gas Water Heater Performance)

Laboratory and field testing completed in this study confirm that tankless water heater performance is affected by low volume draws, as well as the time interval between draws. In the lab testing we have completed test with “hot” and “cold” heat exchangers. The projected impact on efficiency under an assumed load profile is fairly significant, ranging from an average “daily” efficiency of 70.3% for a cold heat exchanger to 77.3% for a hot heat exchanger. In reality, the expected degradation will lie somewhere between these two points. Given the lack of solid data on hot water usage patterns, load magnitude, and time between draws, we propose applying a 40% weighting factor to “cold” and a 60% weighting to “hot”. The resulting seasonal efficiency is calculated to be 74.5%, or 8.8% below the nominal 81.6% efficiency.

Our recommendations for ACM rules in regards to tankless water heaters are as follows:

- The ACM should degrade the listed Energy Factor for gas tankless water heaters by 8.8%.
- For units with a continuously burning pilot, 500 Btu/hour of pilot energy should be assumed, unless a value is available in the CEC’s Appliance Directory for small natural gas instantaneous water heaters.

The proposed 8.8% Energy Factor degradation would be uniformly applied in the ACM, regardless of the magnitude of the hourly hot water load. Although this approach is technically not accurate on a “per draw” basis (smaller draws have larger performance degradation and large draws have little or no degradation), the proposed approach does provide accurate answers on a daily or annual time scale. In addition, given the lack of knowledge on hot water usage patterns in California, it is premature to propose a more detailed modeling methodology that could focus on time steps shorter than the current one hour interval used in the ACM.

HWDS Pressure Loss Report

For the six houses studied we found that pressure loss due to friction and vertical rise was not the determining factor in whether incrementally smaller diameter systems would be acceptable. Excessive hot water velocity occurred before pressure loss in a particular smaller system became a limiting factor. Some of the incrementally smaller systems exceeded the generally accepted 5 ft/sec maximum hot water velocity for copper pipe and 10 ft/sec overall code maximum. Limiting velocity is used to reduce the erosive corrosion on both copper and plastic pipes, and, to a lesser degree, to reduce the noise.

The study calculated the friction loss of the plumbing pipes at about 30% of the total loss the remaining 70% was due to vertical rise. It is found, by using the Bernoulli’s equation, with the assumption of the hot water pipe total loss, including rises and friction losses, 25 psi inlet water pressure is more than enough to provide needed volume of hot water, if the total loss is not excessive.

We found that because CPVC pipes, with the same nominal sizes as that of copper pipes, have larger inside diameters, they can have higher flow rates and yet still within the maximum hot water velocity allowed. On the other hand PEX of the same nominal size has smaller interior diameter than both CPVC and copper and thus the velocity is higher for a given flow. Reducing the branch serving a lavatory/sink (1.5 GPM) to 3/8” is acceptable for all materials. For a shower (2.5 GPM) the branch could also be reduced to 3/8” if CPVC or PEX were utilized. For flows of 4.0 GPM (some mains) a 1/2” line is adequate if CPVC or PEX were used. For mains with a flow rate of 6.5 GPM a 1/2” CPVC pipe is also adequate.

These potential pipe size reductions may appear small, but they would reduce the entrained hot water volume by approximately 40%. This reduction would proportionately speed the arrival of hot water to the end use fixture as well as reduce the volume of water to be wasted awaiting the arrival of hot water.

4.1.5. Validate HWDS Simulation Models

The HWSIM model was validated against available “in air” test data provided by Applied Energy Technology. Key conclusions include:

- With a minor adjustment of the inside heat transfer coefficient, the program generates a good match with AET data for “during flow” heat transfer for all pipe materials and through a range of flow rates.

- HWSIM does not demonstrate the same degree of sensitivity in AF/PV to pipe length and flow rate as the lab data, however, on average it is fairly close to the lab data for typical residential hot water flow rates (1-3 GPM).
- Decay results are acceptable, but could warrant additional evaluation in the next phase of the PIER LBNL hot water study. The overall impact of thermal decay between draws is dependent on several factors including usage profiles, plumbing configuration, and environment conditions.

4.1.6. Complete CASE Initiatives for Single Family Water Heating

Tankless Gas Water Heaters

Our recommendations for updating the ACM rules for tankless water heaters include the following:

- The ACM should degrade the listed Energy Factor for gas tankless water heaters by 8.8%.
- For units with a continuously burning pilot, 500 Btu/hour of pilot energy should be assumed, unless a value is available in the CEC's Appliance Directory for small natural gas instantaneous water heaters.

The proposed 8.8% Energy Factor degradation would be uniformly applied in the ACM, regardless of the magnitude of the hourly hot water load. Although this approach is technically not accurate on a "per draw" basis (smaller draws have larger performance degradation and large draws have little or no degradation), the proposed approach provides accurate results on a daily or annual time scale. Given the current lack of knowledge on hot water usage patterns in California, it is premature to propose a more detailed modeling methodology that would hopefully utilize shorter time steps than the current one hour interval used in the ACM.

Revise ACM Distribution System Multipliers and Eligibility Requirements

The following recommended changes to the 2005 Building Energy Efficiency Standards were submitted to the Energy Commission. All ACM language are shown in red font.

Proposed Revisions to ACM Distribution System Multipliers

Table 13. ACM Distribution System Multipliers

Measure	DSM Now	DSM Proposed
PIA	0.90	<u>0.9</u>
<u>PS*</u>	-----	<u>3.8</u>
<u>PSJ**</u>	-----	<u>1.0</u>
POU	0.00	<u>0.0</u>
STD	1.00	<u>1.0</u>
SNI	1.19	<u>1.2</u>
PP	1.04	<u>1.0</u>
RNC	4.52	<u>4.5</u>
RTm	3.03	<u>3.0</u>
RTmp	3.73	<u>3.7</u>
RTmTmp	2.49	<u>2.5</u>

* PS is piping system buried in soil – delete this entry if made mandatory

** PSI is piping system buried in soil with insulation – delete this entry if made mandatory

Proposed Eligibility Requirements Changes:

Pipe Insulation Eligibility Requirements

Pipe insulation on the first five feet of hot and cold water piping from storage gas water heaters, recirculating sections of domestic hot water systems, all in-soil hot water piping, and the hot water line from the water heater to the kitchen sink and dish washer (regardless of pipe size) is a mandatory measure as specified in Section 150 (j) of Title 24, Part 6. Note that exceptions 3, 4 and 5 to Section 150 (j) apply to all pipe insulation that is required to meet the mandatory measure requirement or that is eligible for compliance credit.

Pipe insulation credit available if all remaining hot water lines are insulated. Insulation shall meet mandatory minimums in Section 150 (j). Pipe insulation must be installed in a manner to avoid future material shrinkage. During insulation, pipe insulation should be compressed along its length and sealed from one length to the next. Pipe elbows shall be insulated, taped, and sealed to adjacent pipe sections.

Add the following if not made mandatory – Pipe insulation credit is available if all hot water lines buried in soil are insulated. Insulation shall meet mandatory minimums in Section 150 (j).

Point of Use Water (POU) Water Heaters Eligibility Requirements

Current requirements apply. All hot water fixtures in the dwelling unit, with the exception of the clothes washer, must be located within 8' (plan view) of a point of use water heater. To meet this requirement, most houses will require multiple POU units.

Recirculation Systems Eligibility Requirements

All recirculation systems must have minimum nominal R-4 pipe insulation on all supply and return recirculation piping. Recirculation systems may not take an additional credit for pipe insulation.

As a general rule, the recirculation loop should be laid out to be within 8 feet (plan view) of all hot water fixtures in the house (with the exception of the clothes washer). The plumbing layout should be focused on minimizing the total volume in the recirculating loop. Remote hot water use points should have longer runouts than 8 feet to avoid overextending the loop.

Approved recirculation controls include “no control”, timer control, time/temperature control, and demand control. Time/temperature control must have an operational timer initially set to operate the pump no more than 16 hours per day. Temperature control must have a temperature sensor with a minimum 20°F deadband installed on the return line.

Demand recirculation systems shall have a pump (maximum 1/8 hp), control system, and a timer or temperature sensor to turn off the pump in a period of less than 2 minutes from pump activation. ~~Acceptable control systems include push buttons, occupancy sensors, or a flow switch at the water heater for pump initiation.~~ At a minimum, push buttons ~~and occupancy sensors~~ must be located in the kitchen, ~~and in the master bathroom, and all additional full bathrooms.~~

Parallel Piping Eligibility Requirements

Each hot water fixture is individually served by a line, no larger than ½ in., originating from a central manifold located no more than ~~8 10 pipe~~ feet from the water heater. The entire pipe from water heater to manifold must have minimum nominal R-4 pipe insulation. Fixtures, such as adjacent bathroom sinks, may be “doubled up” if fixture unit calculations in Table 6-5 of the California Plumbing Code allow.

Acceptable piping materials include copper and cross-linked polyethylene (PEX), depending upon local jurisdictions.

3/8 in. lines are ~~acceptable encouraged~~, pending local code approval, provided minimum required ~~pressures flow rates~~ listed in the California Plumbing Code (Section 608.1) can be maintained.

~~Piping to the kitchen fixtures (dishwasher and sink(s)) that is equal to or greater than ¾ inch in diameter must be insulated to comply with Section 151(f)8D.~~

PEX Parallel Piping Hot Water Distribution Systems

The proposal for improving parallel piping HWDS performance by limiting water heater to manifold length and requiring insulation on the line has very favorable economics. Additional non-quantified benefits of reduced water consumption, reduced piping material needs, and increased homeowner satisfaction (reduced distribution losses and hot water waiting times) all point to a strong endorsement for this proposal to become a mandatory measure.

The following change, highlighted in blue, is proposed for the Building Energy Efficiency Standards (Subchapter 7, Section 150 (j) 2).

- (j) Water System Pipe and Tank Insulation and Cooling Systems Line Insulation.
 - 1. Storage tank insulation.
 - A. Storage gas water heaters with an energy factor < 0.58 shall be externally wrapped with insulation having an installed thermal resistance of R-12 or greater.
 - B. Unfired hot water tanks, such as storage tanks and backup storage tanks for solar water-heating systems, shall be externally wrapped with insulation having an installed thermal resistance of R-12 or greater or have internal insulation of at least R-16 and a label on the exterior of the tank showing the insulation R-value.

2. Water piping and cooling system line insulation thickness and conductivity. Piping, whether buried or unburied, for recirculating sections of domestic hot water systems; piping from the heating source to the storage tank for an indirect-fired domestic water-heating system; the first five feet of hot and cold water pipes from the storage tank for nonrecirculating systems; [the entire length of the water heater to manifold piping in parallel piping hot water distribution systems \(maximum piping length of ten feet\)](#) ; and cooling system lines shall be thermally insulated as specified in Subsection A or B. Piping for steam and hydronic heating systems or hot water systems with pressure above 15 psig shall meet the requirements in Table 123-A.

Water and Wastewater Tariffs

We recommend that the value of water saved be included in the cost effectiveness calculation for measures that save water. Based on our preliminary evaluation (described above), we recommend a value of \$2 per HCF (100 cubic feet) to represent the savings in both water and waste water bills to the end user.

We recommend that a new section be added to the compliance manual, in which the savings to the end user are calculated from reduced water consumption and waste water releases due to decreased hot water consumption.

4.2. Support for the Super Efficient Gas Water Heating Appliance Initiative (SEGWHAI)

4.2.1. Gas Water Heater Energy Losses

Reducing heat losses up the flue during standby mode has the greatest potential for increasing water heater efficiency. Reducing jacket and fitting losses, while possibly less complicated to achieve, offer only a modest potential for increases in efficiency.

4.3. Existing Residential Hot Water Distribution Systems

4.3.1. Pilot mail survey of single-family house occupants

Several questions relating to hot water distribution systems were developed and added to the customer survey of the California Single-Family Residential Water Use Efficiency Study. The results of the survey should be accounted for in the development of future standards and research on residential hot water distribution systems.

4.3.2. Determine data needs of regulatory organizations

During our research and the preparation of proposed code changes, it has become clear to us that there is a need for close collaboration between energy and plumbing researchers to investigate and address any outstanding issues or concerns that may arise from the code modification process. Through this collaboration and the increased knowledge it will provide, we are confident that meaningful improvements can be made to the UPC or other applicable codes and standards. These changes will assure appropriate levels of service from hot water distributions systems while minimizing energy and water waste.

4.3.3. Assess potential sensing and monitoring technologies

Past studies have by-and-large had a relatively narrow focus that considered specific issues/topics such as demographics (number of occupants, age, renter/owner), seasonal variation or type of water heater. Temperature-based event studies are more accurate (97.1%) but were not broad based with a very limited sampling of homes. The flow trace signature analysis studies are less accurate (90.6%) but have been larger in scope with significantly more houses evaluated. The Residential End-Use Model (REUM) is based on very limited field data which raises questions of its validity.

Given the limits on current knowledge we conclude that data obtained from a large-scale, accurate (temperature-based) sampling is needed to substantiate the potential energy code (Title 24) and plumbing code (Uniform Plumbing Code) changes. The data is also needed in HWDS optimization simulation studies that could lead to best practices recommendations for system configuration.

The large-scale sampling would be measured in hundreds, if not thousands, of housing units in order to cover the full spectrum of variation that is likely to occur among houses and households. Based on the duration of the flow trace signature analysis studies we feel that a two week sampling of an individual home is adequate. The overall study would extend for 12-24 months in order to collect seasonal variations and permit a large number of homes to be monitored with a limited number of sampling devices.

Given the magnitude of this monitoring effort, the systems must be easy to install, minimally invasive, robust in the home environment, accurate and of reasonable cost. The Assessment of Available Sensing and Monitoring Technologies which follows will evaluate the currently available technologies to address these criteria.

4.3.4. Bench test key elements of sensing and monitoring technologies

The response time between immersion versus wall-mounted thermocouple indicates that immersion systems for measuring temperature should be used on all non-copper systems if a resolution of better than five seconds is desired. If measurement of true water temperature is desired within 5 degrees, then immersion type systems for measuring temperature should be used on all hot water systems.

5.0 References

- W. B. DeOreo and P. W. Mayer, The End Uses of Hot Water in Single Family Homes from Flow Trace Analysis, Aquacraft, Inc., 2002.
- KEMA-XENERGY, Itron, and RoperASW, Residential Appliance Saturation Study, Final Report Executive Summary, California Energy Commission, Sacramento 400-04-009, June 2004.

6.0 Glossary

ACM	Alternative Calculation Method
AET	Applied Energy Technology Co.
AF/PV	Actual Flow to Pipe Volume ratio. The amount of water wasted while waiting for hot-enough-to-use water to arrive at fixtures.
CASE	Codes And Standards Enhancement
CPVC	Chlorinated Polyvinyl Chloride
DSM	Distribution System Multipliers
DHW	Domestic Hot Water
FD&D	Fault Detection and Diagnostics
GPM	gallons per minute
HARL	Hourly Adjusted Recovery Load
HDPE	high-density polyethylene
HRDL	Hourly Recirculation Distribution Loss
HMG	Heschong Mahone Group
HCF	hundred cubic feet
HWDS	Hot Water Distribution System
HWSIM	domestic Hot Water system SIMulation model
IAPMO	International Association of Plumbing and Mechanical Officials
LabVIEW	Laboratory Virtual Instrumentation Engineering Workbench
LBNL	Lawrence Berkeley National Laboratory
MF	Multifamily
NAHBRC	National Association of Home Builders Research Center
NO _x	Generic term for the nitrogen oxides NO and NO ₂
ORNL	Oak Ridge National Laboratory
PEX	Cross-linked Polyethylene
PIER	Public Interest Energy Research
PM	Performance Monitoring

PSI	Pounds per Square Inch
PVC	Polyvinyl Chloride
REUM	Residential End-Use Model
RD&D	Research, Development and Deployment
R&D	Research and Development
SCAQMD	South Coast Air Quality Management District
SEGWHAI	Super Efficient Gas Water Heating Appliance Initiative
TANK	An interactive personal computer program to aid in the design and analysis of gas-fired storage-type water heaters
UPC	Uniform Plumbing Code
WSFU	Water Supply Fixture Units

Appendices

- Appendix A. Multifamily Water Heating Construction Practices, Pricing and Availability Survey Report
- Appendix B. Multifamily Water Heating Controls Performance Field Report
- Appendix C. Pipe Heat Loss Testing
- Appendix D. Single Family Water Heating Construction Practice Survey
- Appendix E. HWDS Materials and Equipment Suppliers Survey
- Appendix F. Current Trends in California Single Family New Construction
- Appendix G. Single Family Prototype Floor Plans and Piping Layouts
- Appendix H. Hot Water Draw Patterns: Findings from Field Studies
- Appendix I. Water and Wastewater Tariff Report
- Appendix J. Ground Heat Transfer Algorithm Report
- Appendix K. Instantaneous Gas Water Heater LDEF Report (Field and Laboratory Testing of Tankless Gas Water Heater Performance)
- Appendix L. HWDS Pressure Loss Report
- Appendix M. HWSIM Hot Water Distribution Model Validation Report
- Appendix N. Measure Information Template: Tankless Gas Water Heaters
- Appendix O. Measure Information Template: Revise ACM Distribution System Multipliers and Eligibility Requirements
- Appendix P. Measure Information Template: PEX Parallel Piping Hot Water Distribution Systems
- Appendix Q. Measure Information Template: Water and Wastewater Tariffs
- Appendix R. Gas Water Heater Energy Losses
- Appendix S. Household Water Use Survey
- Appendix T. Residential Hot Water Distribution System Research Suggests Important Code Changes
- Appendix U. Assess Potential Sensing and Monitoring Technologies
- Appendix V. Bench Test Key Elements of Sensing and Monitoring Technologies